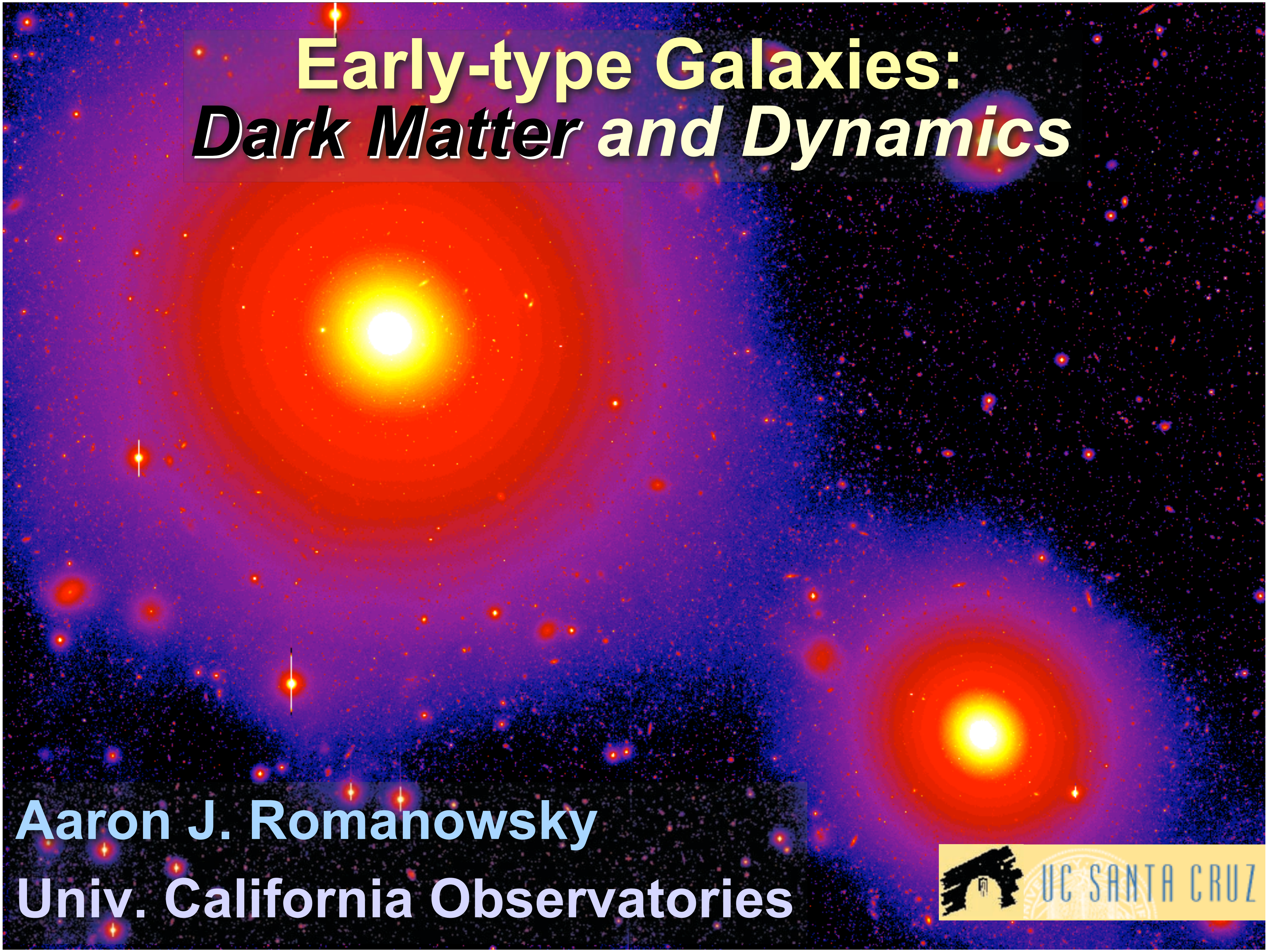


Early-type Galaxies: *Dark Matter and Dynamics*

Aaron J. Romanowsky
Univ. California Observatories
UC SANTA CRUZ

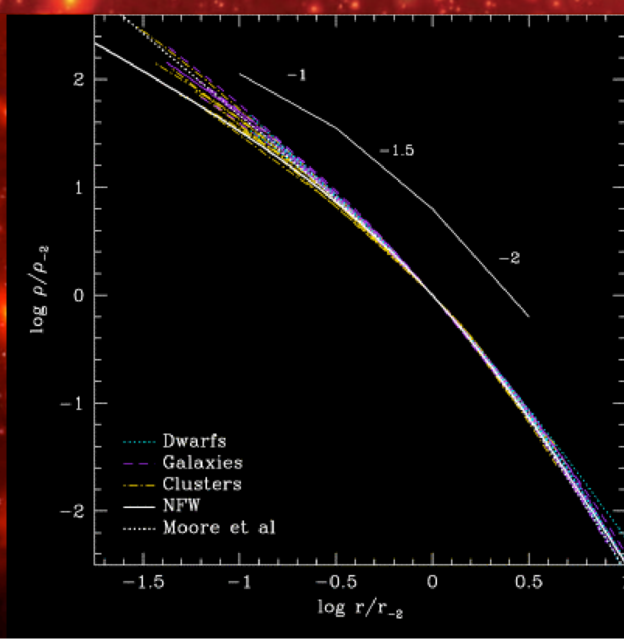
Inventory of DM in galaxies

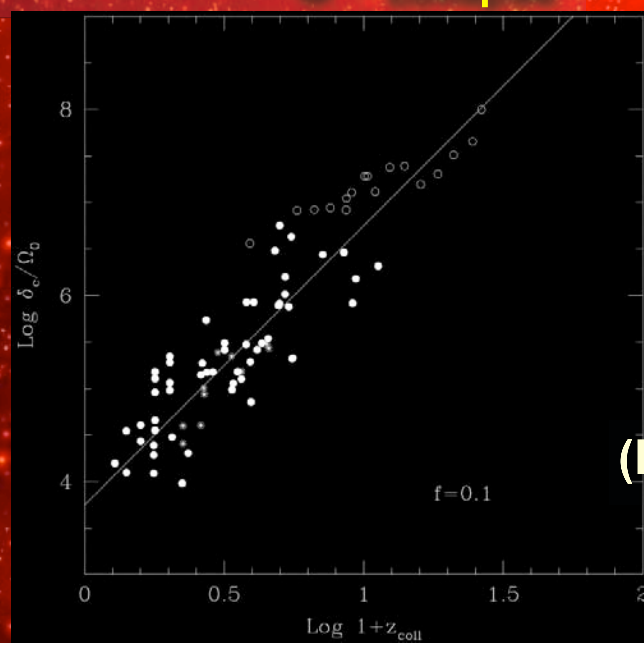
Detailed observational constraints:

- **Test ΛCDM paradigm**
- **Constrain nature of DM**
- **Probe galaxy formation**

Unique properties of CDM halos:

- ***dN/dM_{vir}***
- **central density cusp: $\rho(r) \sim r^{-\alpha}$, $\alpha \sim$ 1-1.5**
- **mass-density relation reflecting $z_{collapse}$**

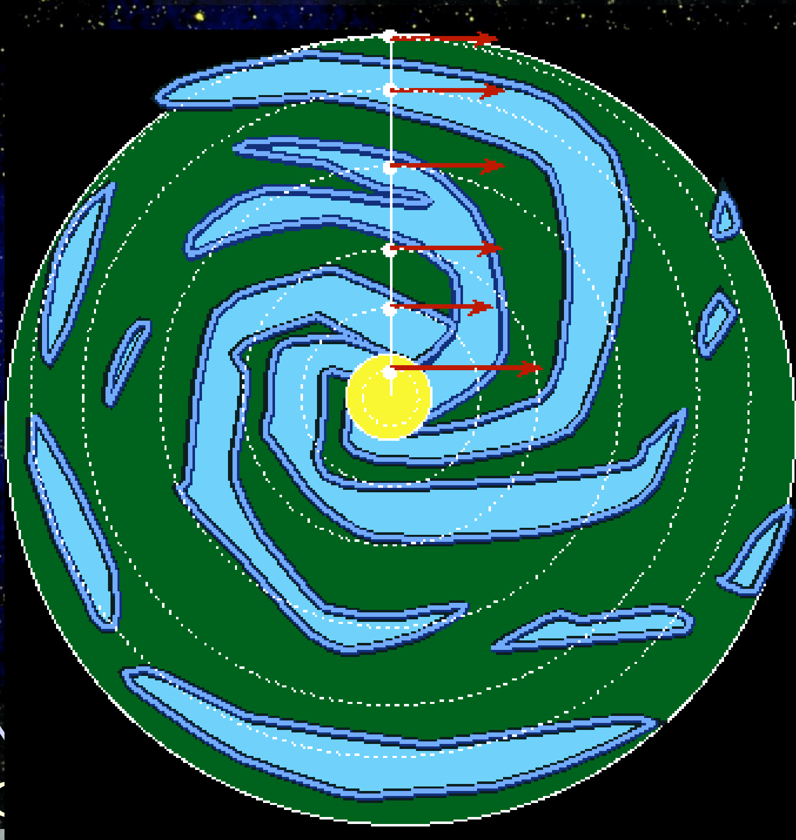




(Navarro et al. 1997, 2004)

"Via Lactea 2" simulation
(Diemand et al. 2008)

Late-type galaxies: mass from gas



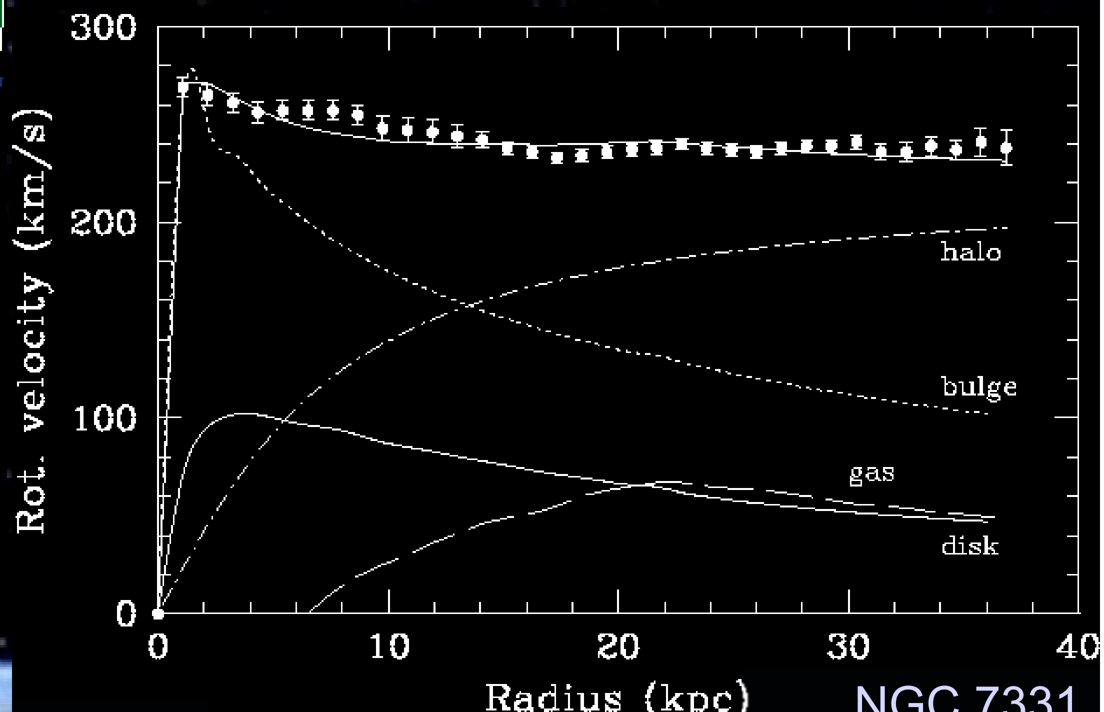
Rotation curve (circular velocity):

$v_c(r) \equiv \sqrt{r a_r} = \sqrt{GM(<r)/r}$

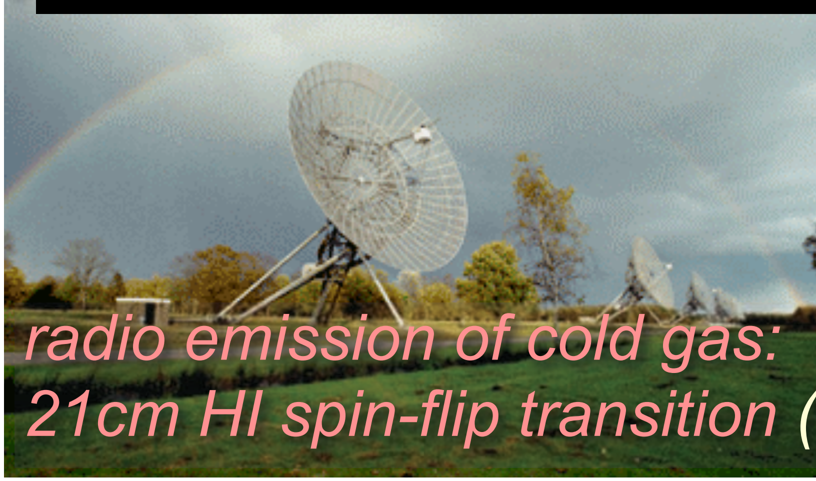
Keplerian: $v_c(r) \sim r^{-1/2}$

Spiral halos: $v_c(r) \sim$ const

$\Rightarrow M(<r) \propto r$: *dark matter!*



NGC 7331
(Bottema 1999)



radio emission of cold gas:
21cm HI spin-flip transition (1970s)

Disk/halo degeneracy

*L** spirals

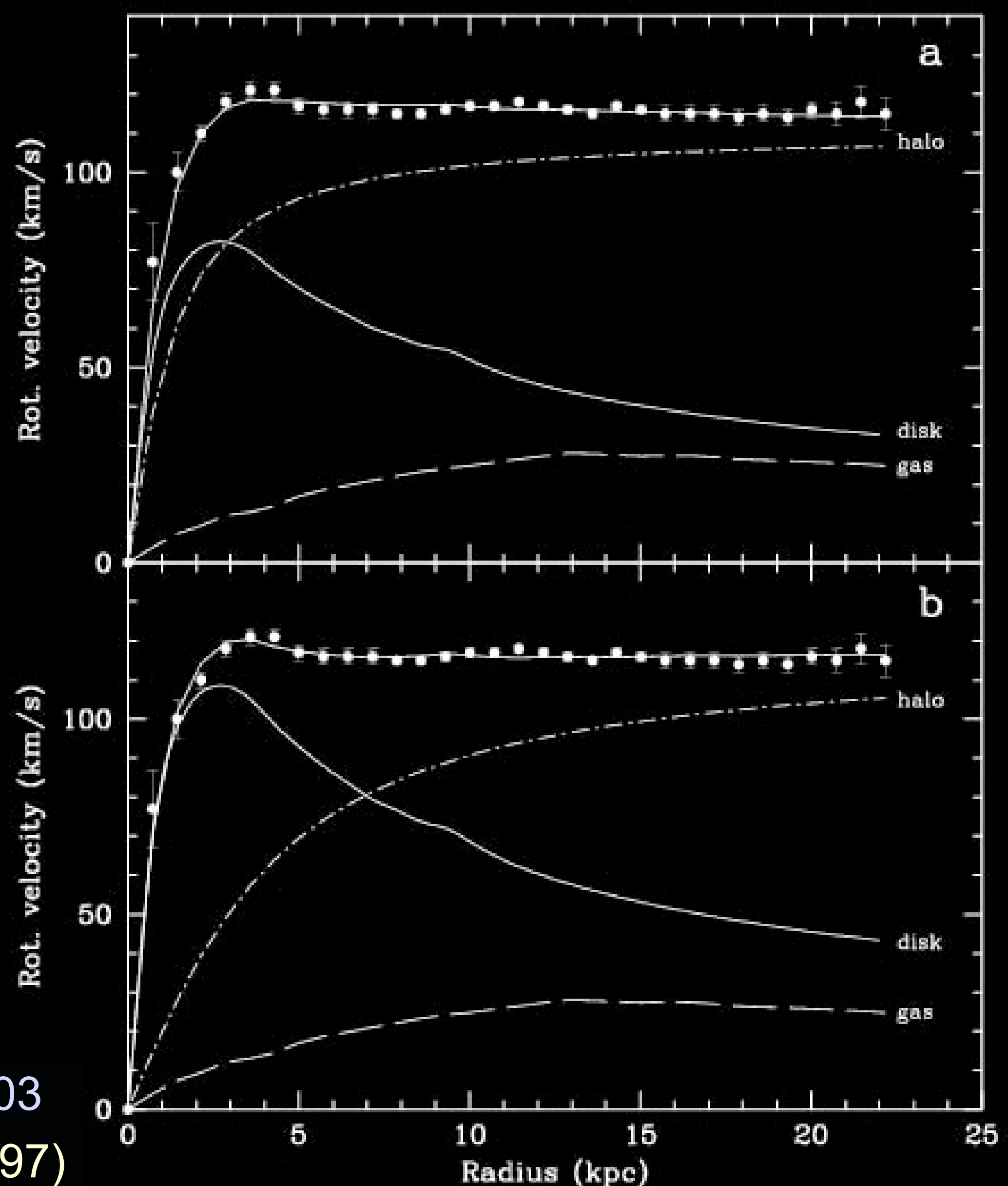
HI rotation curve:

$v_c(r) \equiv \sqrt{GM/r}$

constant at large *r*

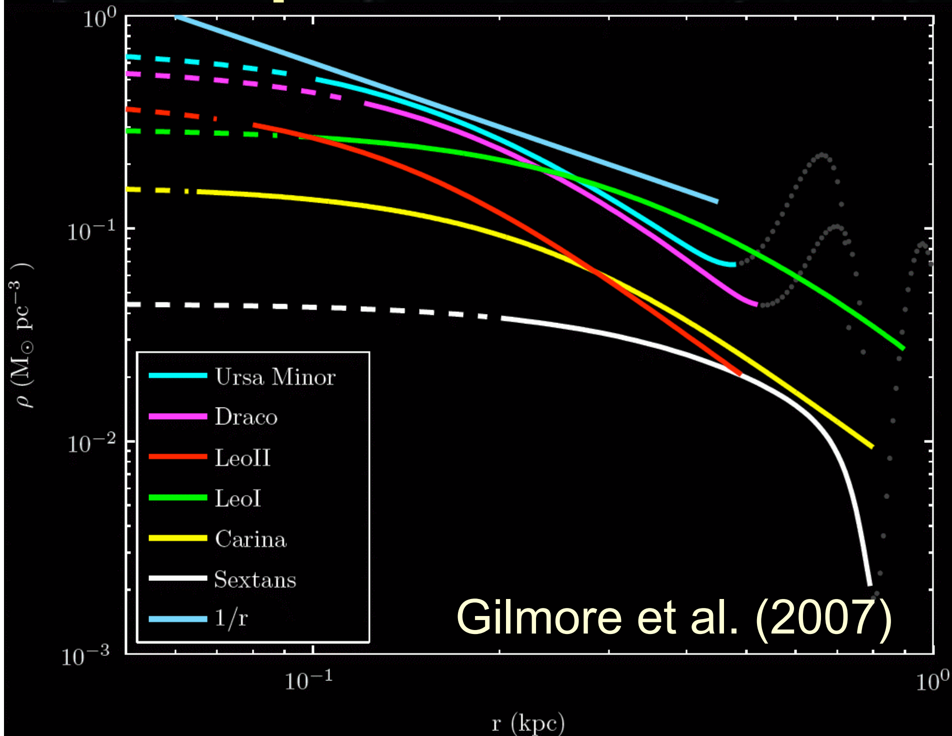
(Persic et al. 1996)

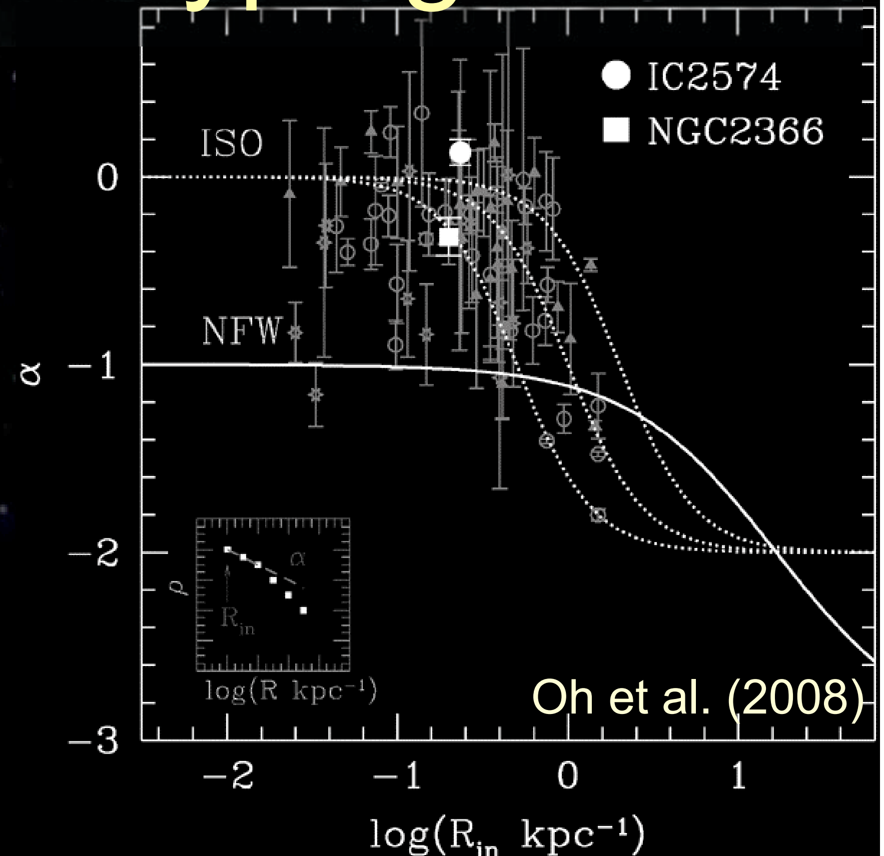
But shape of inner halo profile dependent on disk M/L

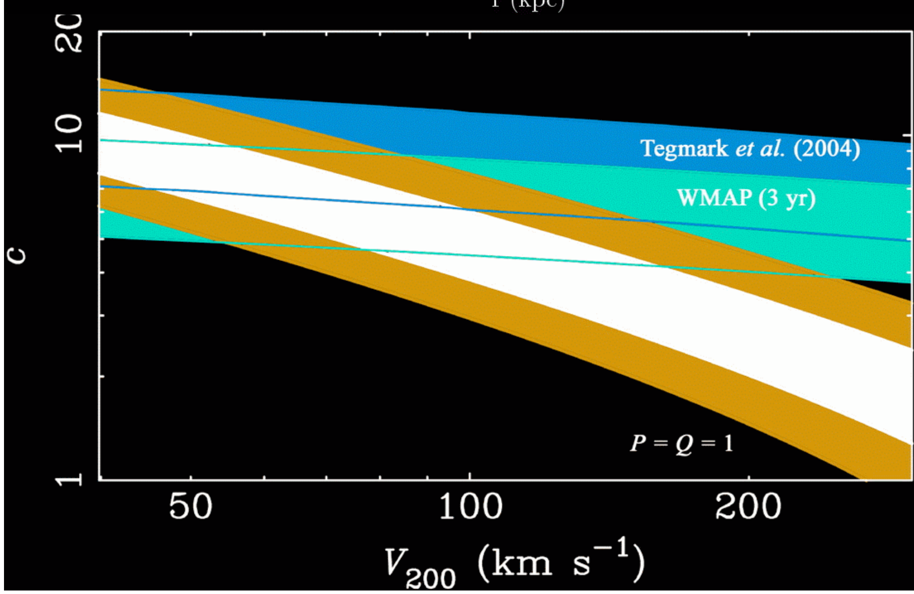


NGC 6503
(Bottema 1997)

DM puzzles from late-type galaxies







- LSBs: cusps not seen
- *L** galaxies: low DM density

$c_{vir} \equiv r_{vir}/r_{-2}$

(Kassin et al. 2006; McGaugh et al. 2007; Dutton et al. 2007; Gnedin et al. 2007)

DM probes in early-type galaxies

- kinematics
  - resolved stars (TMT!)
  - integrated stellar light
  - planetary nebulae (PNe)
  - globular clusters (GCs)
- X-ray emission
- gas disks & rings (HI & Hα)
- strong gravitational lensing
- weak gravitational lensing
- satellite dynamics

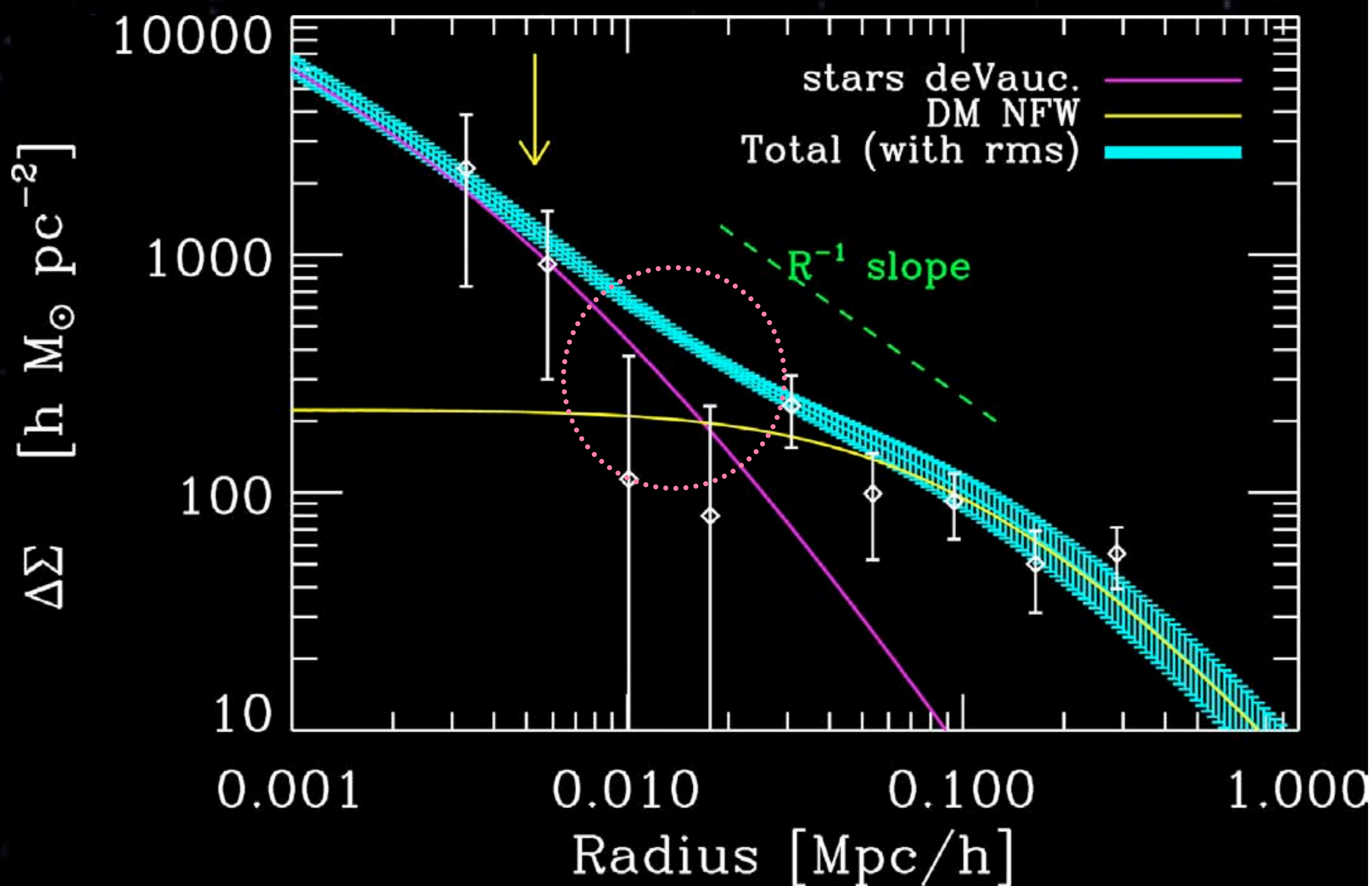
} *ideal probes* (kinematics)

} *selection effects* (X-ray emission; gas disks & rings; strong gravitational lensing)

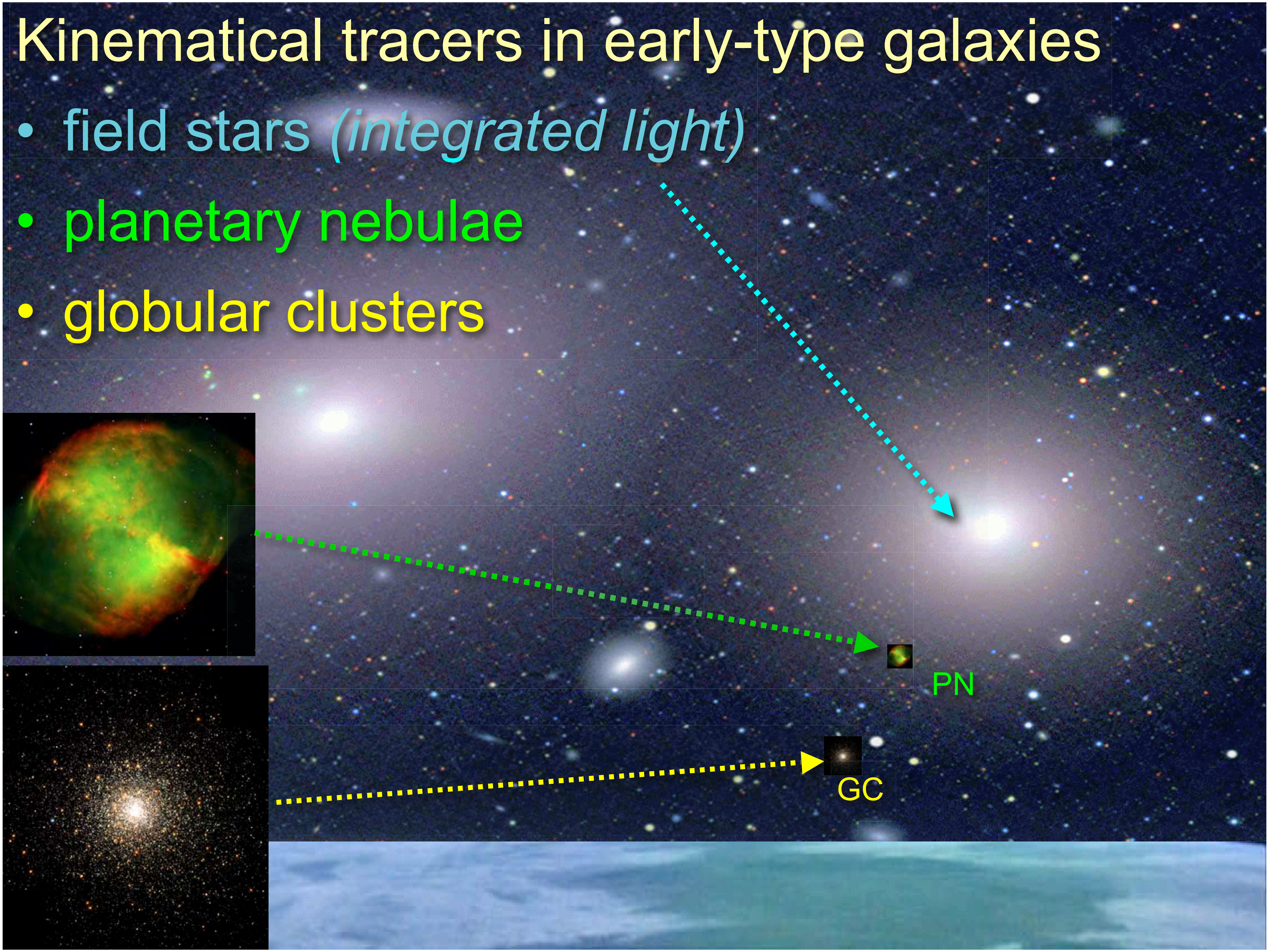
} *statistical only* (weak gravitational lensing; satellite dynamics)

DM in early-types: weak+strong lensing

22 bright E/S0s at z ~ 0.2 (SLACS: Gavazzi et al. 2007)



- *halo concentration, inner slope not constrained*
- *σ_c< 200 km/s (fast rotators) not well constrained*


Kinematical tracers in early-type galaxies
• field stars (integrated light)
• planetary nebulae
• globular clusters
PN
GC

Theory testing

• Data
⇒ fit (parametrized) models
⇒ compare to theory

E.g. kinematics
⇒ mass, orbit profiles
⇒ compare ΛCDM

Questions about model assumptions: geometry, equilibrium, uniqueness, oversimplification…

• Theory
⇒ "observe" (parametrized)
⇒ compare to data

E.g. simulated galaxies
⇒ luminosity, velocity profiles
⇒ compare to data

Need large data sample + suitable parameters incl. correlations…

Kinematics → Dynamics → Mass

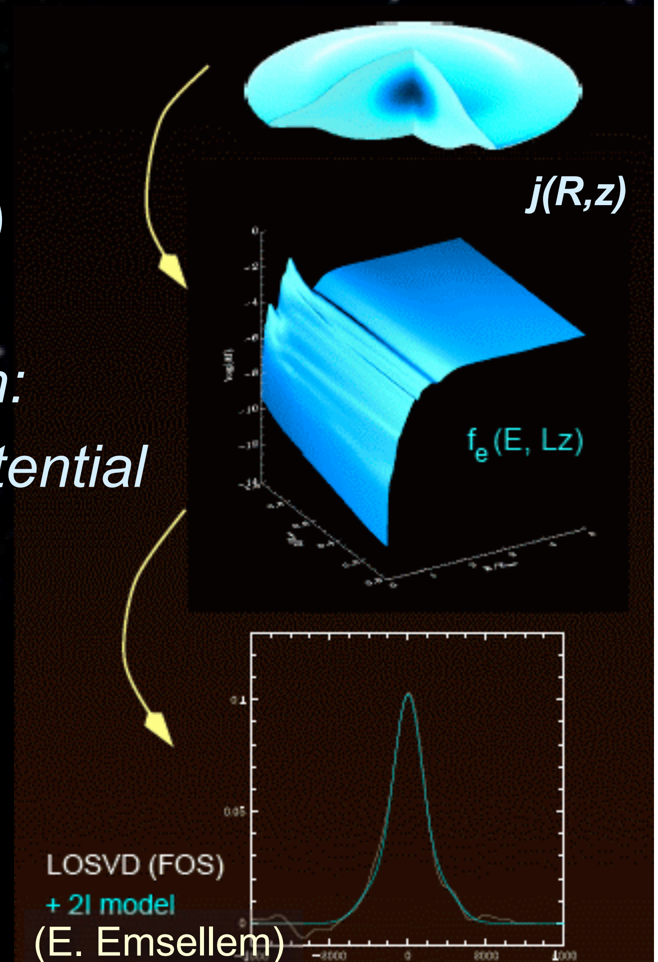
Distribution Function *(6-D position-velocity phase space)*

$$\int d^3\mathbf{x}\, d^3\mathbf{v}\, f(\mathbf{x},\mathbf{v},t) = 1$$ *separate for subpopulations (metallicity, age…)*

$$\nu(\mathbf{x}) \equiv \int d^3\mathbf{v}\, f(\mathbf{x},\mathbf{v})$$ *spatial density*

$$\frac{df}{dt} = 0$$ *incompressible fluid (collisionless)*

$$\frac{\partial f}{\partial t} + \mathbf{v}\cdot\frac{\partial f}{\partial \mathbf{x}} - \nabla\Phi\cdot\frac{\partial f}{\partial \mathbf{v}} = 0$$ *Boltzmann equation: connect to grav. potential*



Jeans theorem: DF described by "integrals of motion" I_i : conserved quantities along orbit *(spherical: energy, angular momentum)*

$$\frac{d}{dt} I[\mathbf{x}(t),\mathbf{v}(t)] = 0$$

Dynamical modeling approaches

- *Projected mass estimators*

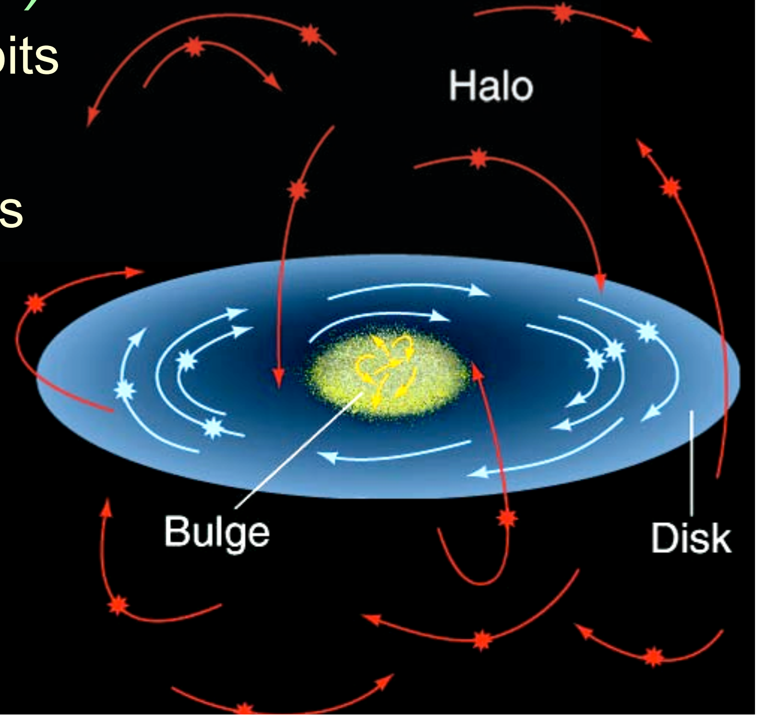
  small # discrete velocities; based on Virial Theorem **$W = -2K$**
- *Jeans equations*

  moments of DF; assume equilibrium
- *Direct DF construction*

  numerical superposition of DF basis functions
- *Orbit models ("Schwarzschild's method")*

  numerical superposition of stationary orbits
- *Particle models ("made-to-measure")*

  numerical superposition of evolving orbits

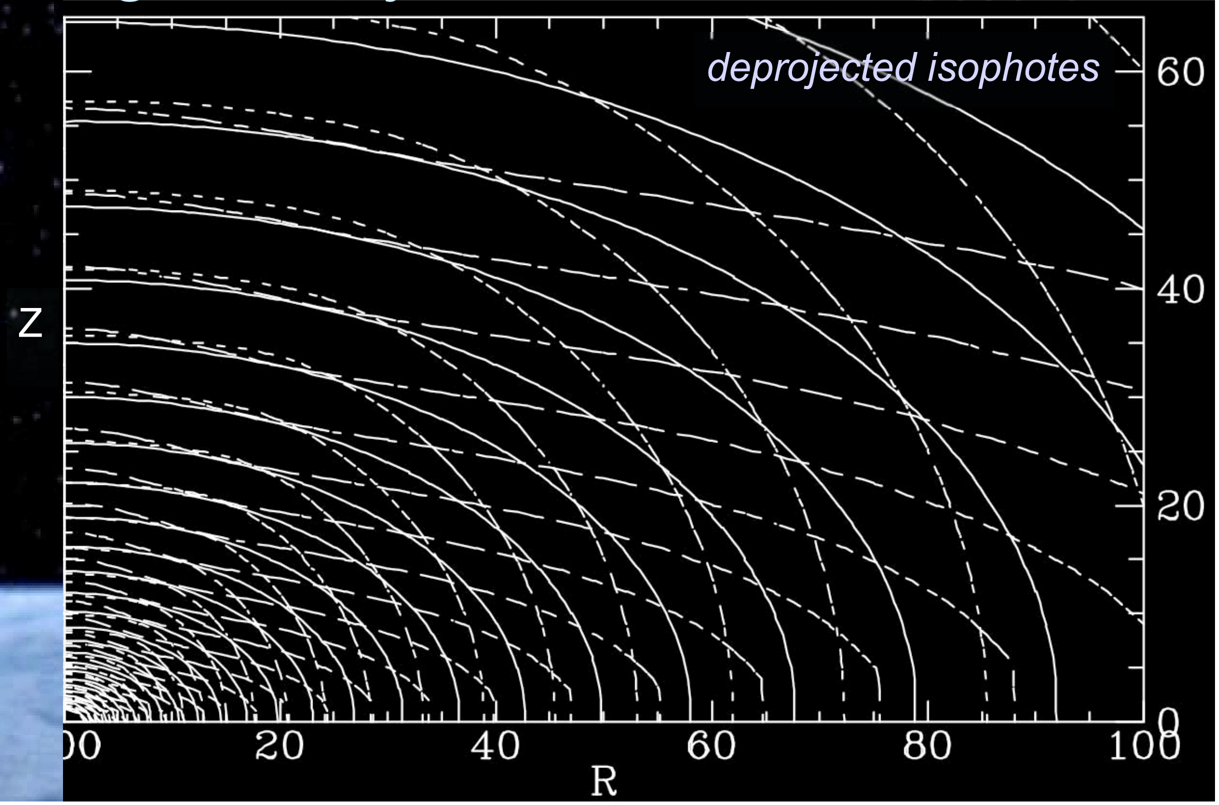


Dynamical modeling challenges

- ***Unbiased tracers of DF for space + velocity***
- ***Information loss in projection:***
  - konus (luminosity) degeneracy
    (Rybicki 1987; Gerhard & Binney 1996; Kochanek & Rybicki 1996; Romanowsky & Kochanek 1997)
  - mass-anisotropy degeneracy

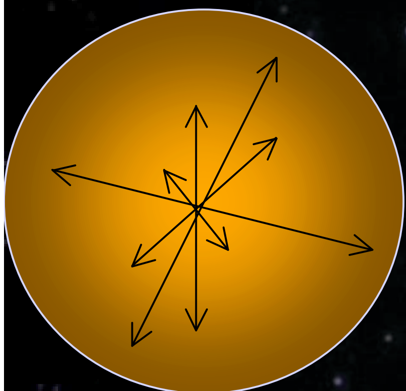
- In spherical system, complete info on projected DF $f(R_p, v_p)$ in known $\Phi(r)$ determines true DF
- Constraining Φ + DF unclear

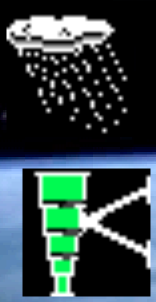
(Dejonghe & Merritt 1992)



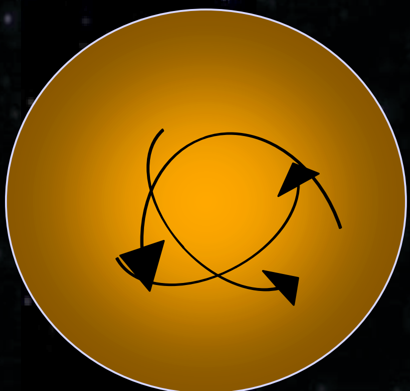
Mass-anisotropy degeneracy

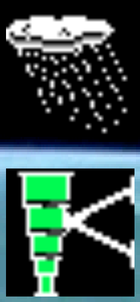
- *Radial orbits*
  - at large *R*, most of the motion in plane of sky
  - lowered velocity dispersion
  - peaked velocity distributions





- *Tangential orbits*
  - at large *R*, much of the motion in line of sight
  - higher velocity dispersion
  - flat velocity distributions





Jeans equations

$$\frac{\partial f}{\partial t} + \mathbf{v} \cdot \frac{\partial f}{\partial \mathbf{x}} - \nabla\Phi \cdot \frac{\partial f}{\partial \mathbf{v}} = 0$$

take moments of Boltzmann eqn

(Jeans 1919)

$$v_c^2 = \frac{GM(r)}{r} = -\sigma_r^2 \left(\frac{d\ln\nu}{d\ln r} + \frac{d\ln\sigma_r^2}{d\ln r} + 2\beta \right)$$

spherical non-rotating Jeans eqn

ν *: tracer density*

σ_r *: radial velocity dispersion*

$\beta(r) \equiv 1 - \sigma_\theta^2 / \sigma_r^2$ *: velocity dispersion anisotropy*

$\beta > 0$ *: radial*

$\beta = 0$ *: isotropic*

$\beta < 0$ *: tangential*

- physical DF not guaranteed
- ν, σ, β often parameterized
- higher-order moments tricky

$$\nu\sigma_r^2 = \int_r^\infty dr' \nu \frac{d\Phi}{dr'} \int_{r'}^\infty 2\frac{\beta(r'')}{r''} dr''$$

solve for known β(r)

$$\sigma_\mathrm{p}^2(R) = \frac{2}{I(R)} \int_R^\infty \left(1 - \beta\frac{R^2}{r^2}\right) \frac{\nu\sigma_r^2 r}{\sqrt{r^2 - R^2}} dr$$

projection to observables

Breaking the mass-anisotropy degeneracy

$$\kappa_{\rm p} \sim \frac{\left\langle v_{\rm p}^4 \right\rangle}{\left\langle v_{\rm p}^2 \right\rangle^2} - 3$$

kurtosis

$$h_l \equiv \frac{\sqrt{2}\gamma_0}{\hat{\gamma}_{\rm p}} \int_{-\infty}^{\infty} \frac{dL}{dv_{\rm p}}(v_{\rm p}) e^{-\hat{w}^2/2} H_l(\hat{w}) dv_{\rm p}$$

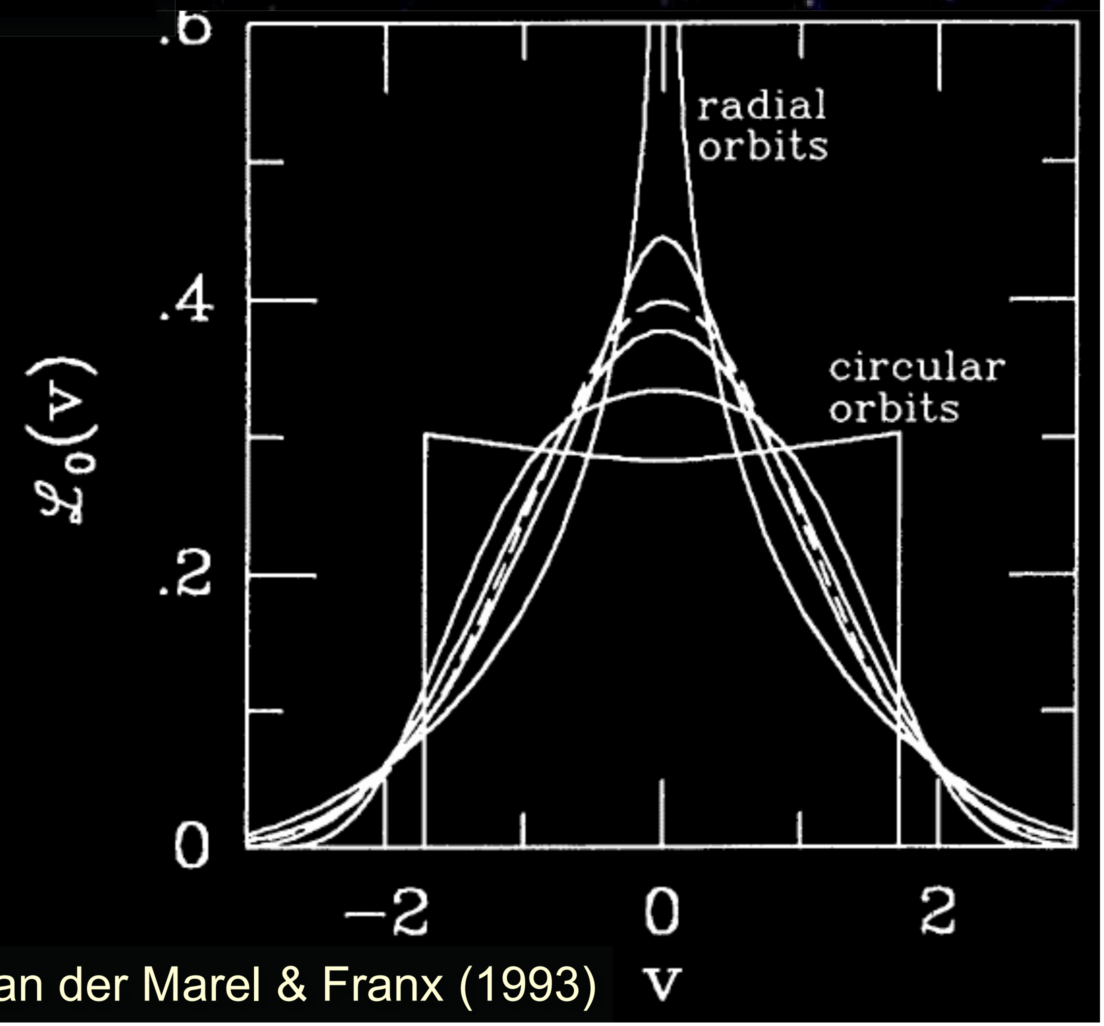
Gauss-Hermite moments $\hat{w} = (v_{\rm p} - \hat{v}_{\rm p})/\hat{\sigma}_{\rm p}$

h_4 , $\kappa_{\rm p}$ measure *shape* of line-of-sight velocity distribution (LOSVD)

h_4 , $\kappa_{\rm p} = 0$: Gaussian;
isotropic orbits

h_4 , $\kappa_{\rm p} > 0$: "peaked";
radial orbits

h_4 , $\kappa_{\rm p} < 0$: "flat-topped";
tangential orbits



van der Marel & Franx (1993)

Higher-order Jeans equations

Assume $f(E,L)=f_0(E)L^{-2\beta}$
$\rightarrow \beta$ constant

(Lokas 2002; Napolitano et al. 2009a)

$$\frac{d}{dr}\left(\nu\left\langle v_r^4\right\rangle\right)+\frac{2\beta}{r}\nu\left\langle v_r^4\right\rangle+3\nu\sigma_r^2\frac{d\Phi}{dr}=0$$

$$\nu\left\langle v_r^4\right\rangle=3r^{-2\beta}\int_r^\infty r'^{2\beta}\nu\sigma_r^2\frac{d\Phi}{dr'}dr'$$ *solution*

$$\left\langle v_{\rm p}^4\right\rangle(R)=\frac{2}{I(R)}\int_R^\infty\left[1-2\beta\frac{R^2}{r^2}+\frac{\beta(1+\beta)}{2}\frac{R^4}{r^4}\right]\frac{\nu\left\langle v_r^4\right\rangle r}{\sqrt{r^2-R^2}}dr$$ *projection*

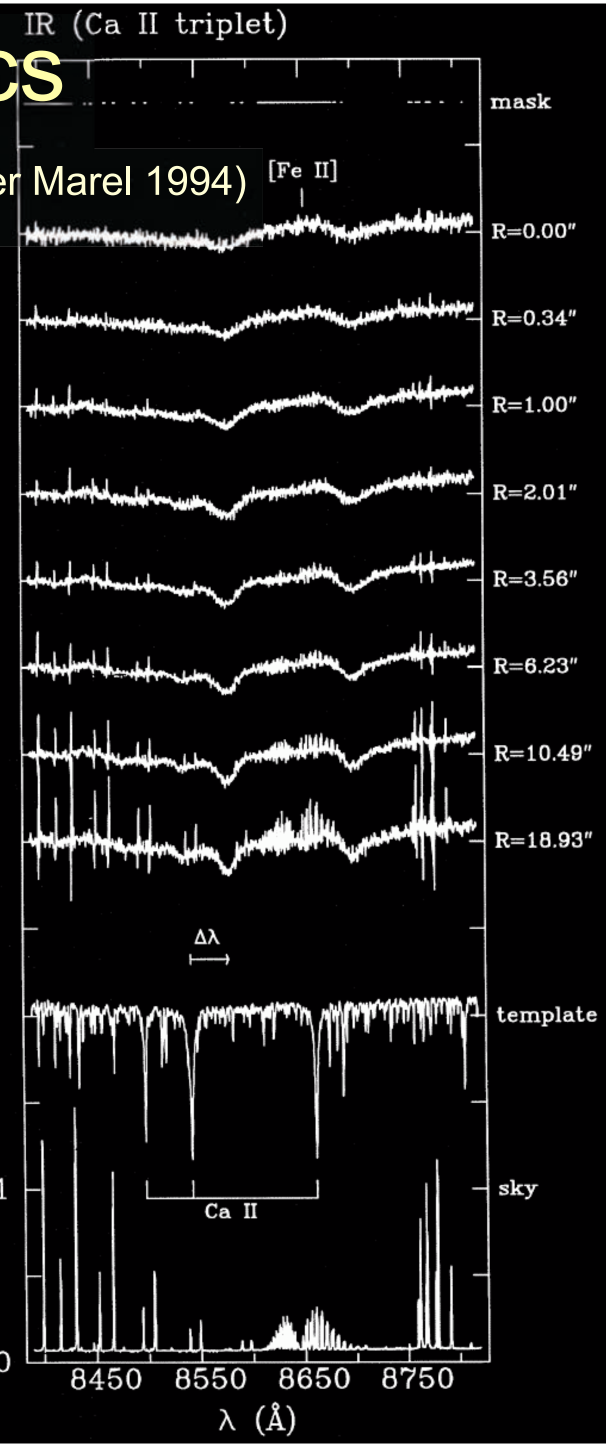
$$\kappa_{\rm p}=\frac{\left\langle v_{\rm p}^4\right\rangle}{\left\langle v_{\rm p}^2\right\rangle^2}-3$$

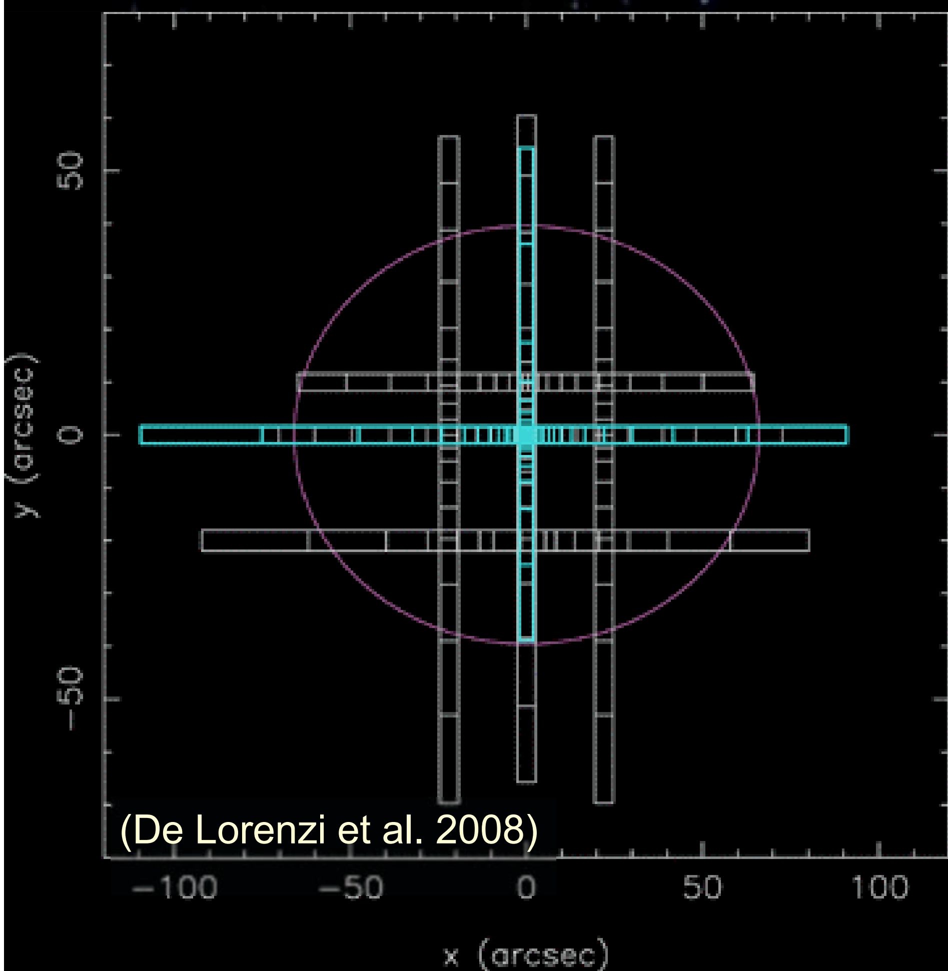
If $\sigma(r)$ const (isothermal), simple expression relating kurtosis, anisotropy, luminosity:

$$\kappa_{\rm p}=3\left(\frac{I_0 I_4}{I_2^2}-1\right)$$

Integrated light stellar kinematics

(van der Marel 1994)



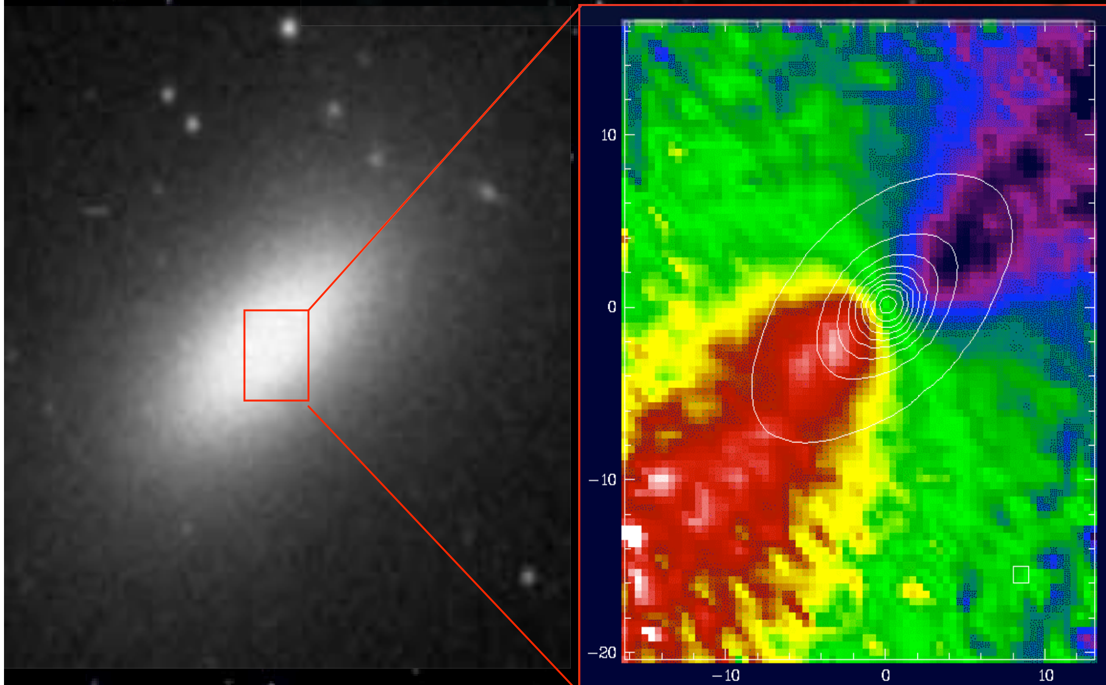


(De Lorenzi et al. 2008)

currently viable to ~ 2 R_{eff}

Long-slit data: cross-correlate template and object spectra → v, σ, h_l as function of radius

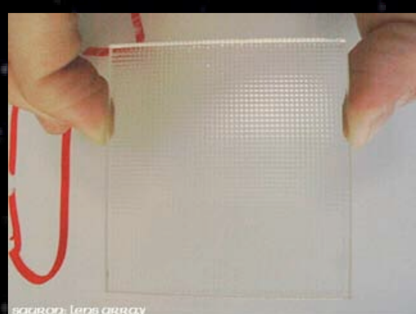
Integral field spectroscopy

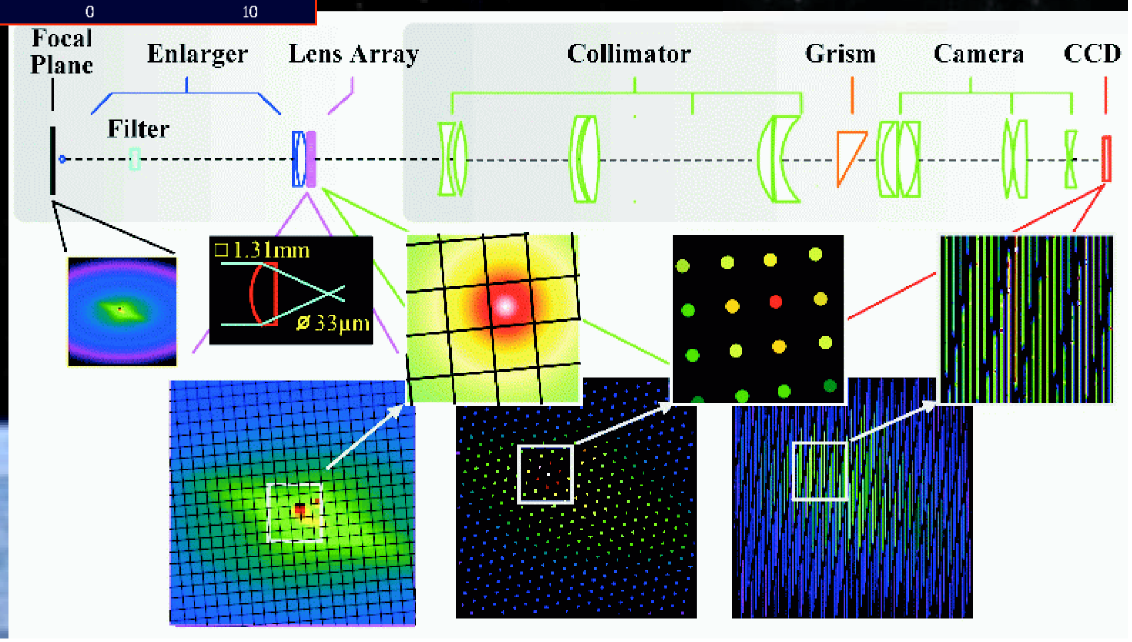


False colour: mean velocity
Contours: surface brightness

currently viable to ~ 1 R_{eff}

(de Zeeuw et al. 2002)



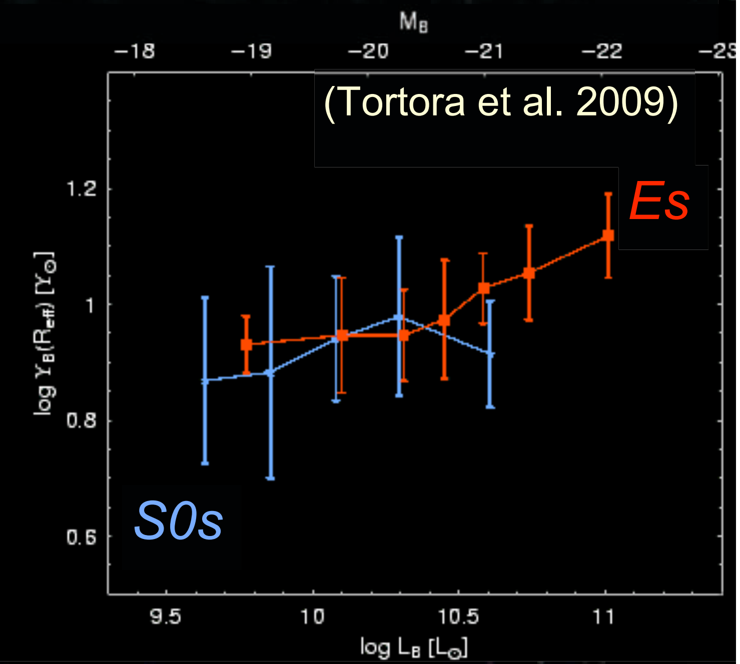


Case study: Jeans eqns + stellar kinematics

335 nearby early-type galaxies observed by Prugniel & Simien (1996)

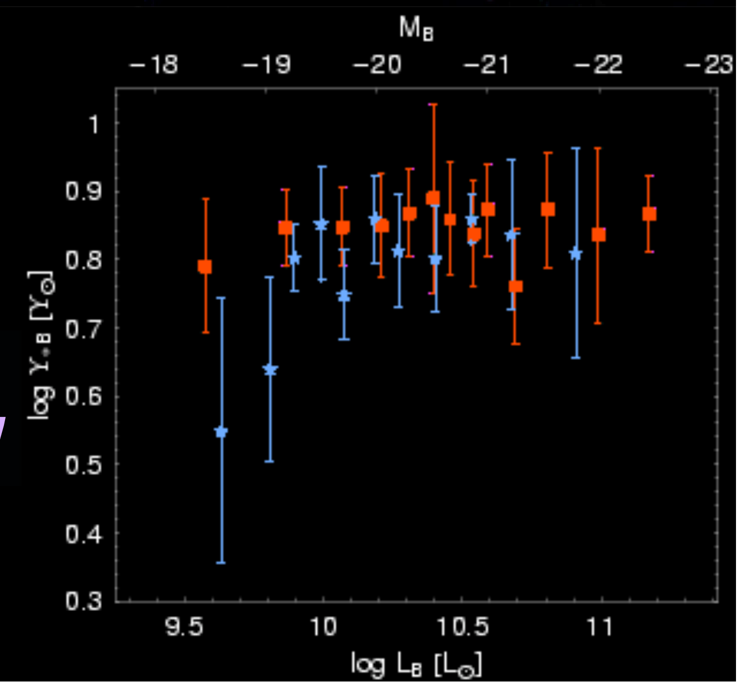
Observables: surface brightness profile $I(R)$, aperture velocity dispersion $\sigma_{Ap}(R)$

Assume mass profile $\rho(r) \sim r^{-2}$, solve Jeans equations to solve for dynamical mass < R_{eff}



Model spectral energy distribution *UBVRI* using stellar populations model (Bruzual & Charlot 2003) with star formation history $e^{-t/\tau}$

Adopt Kroupa IMF, calculate stellar mass

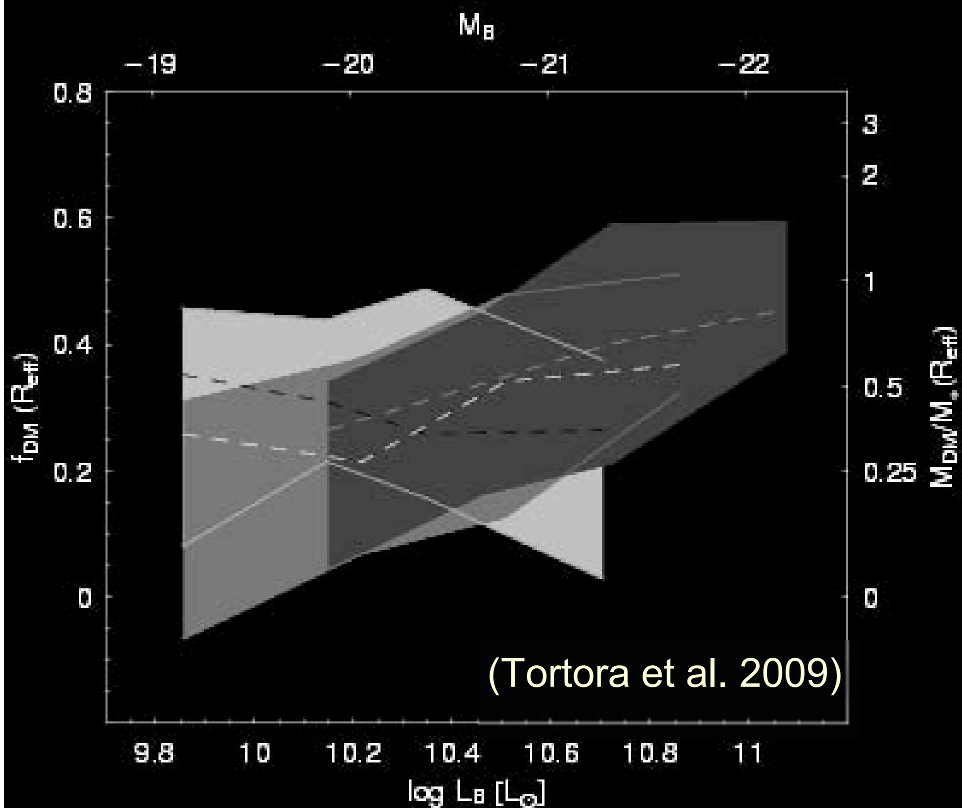


Subtract stellar mass from dynamical mass to get dark mass…

$M/L_{dyn} \sim L^{0.21}$, $M/L_* \sim L^{0.06}$

→ *most of Fundamental Plane "tilt" driven by DM!*

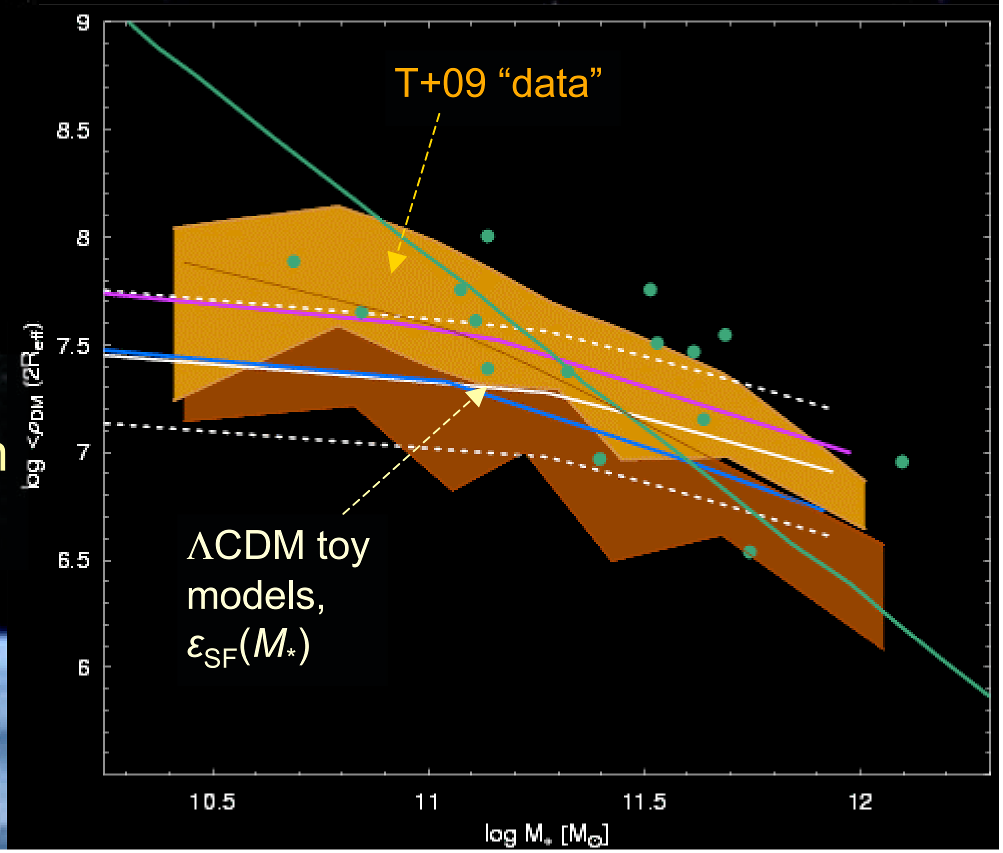
Central dark matter fractions (cont'd)



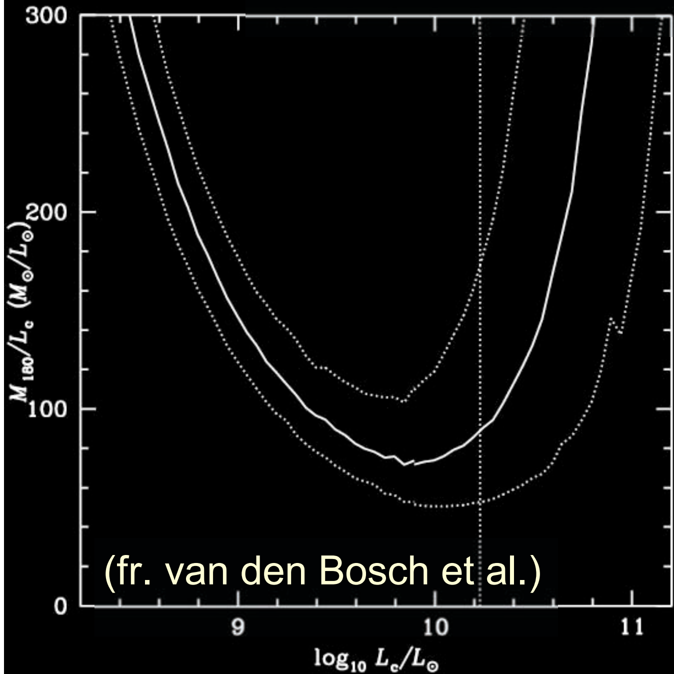
$$f_{DM} \equiv 1 - \Upsilon_* / \Upsilon_{dyn}$$

f_{DM} increases with luminosity, no clear dependence on galaxy sub-type (cf. Cappellari et al. 2006)

central DM density roughly follows ΛCDM expectations, modulo uncertain concentrations and virial masses



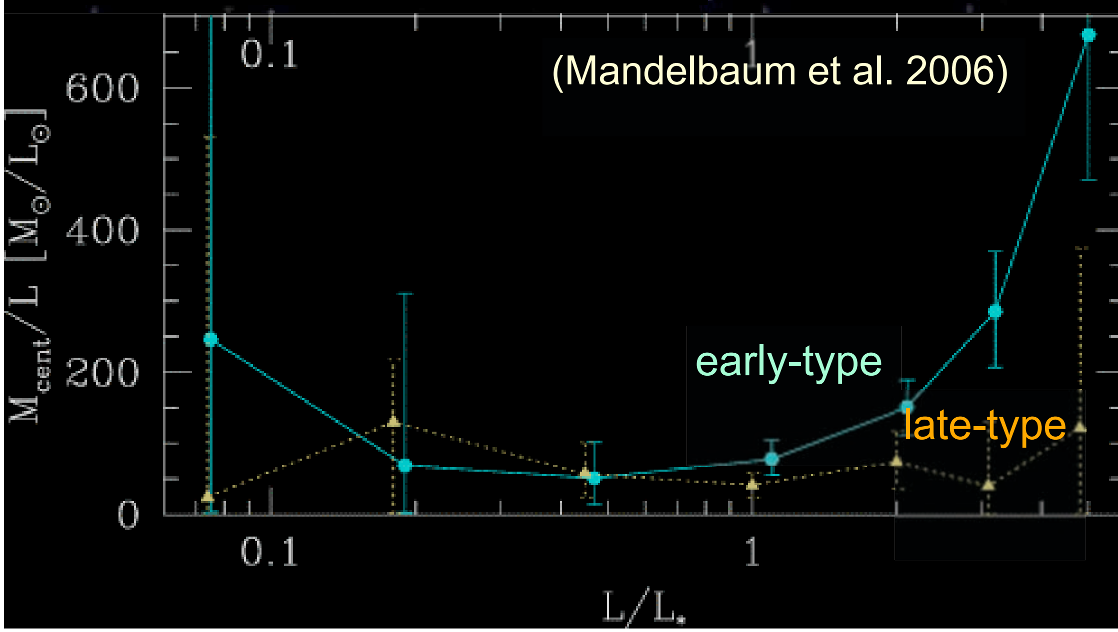
Global dark matter fractions



Virial *M/L* can be rephrased as star formation efficiency $\varepsilon_{SF} \equiv M_* / (f_b M_{vir})$,

U-shaped curve observed:

- "directly" with weak-lensing,
- indirectly by correlating *dN/dL* with theoretical DM halo *dN/dM*

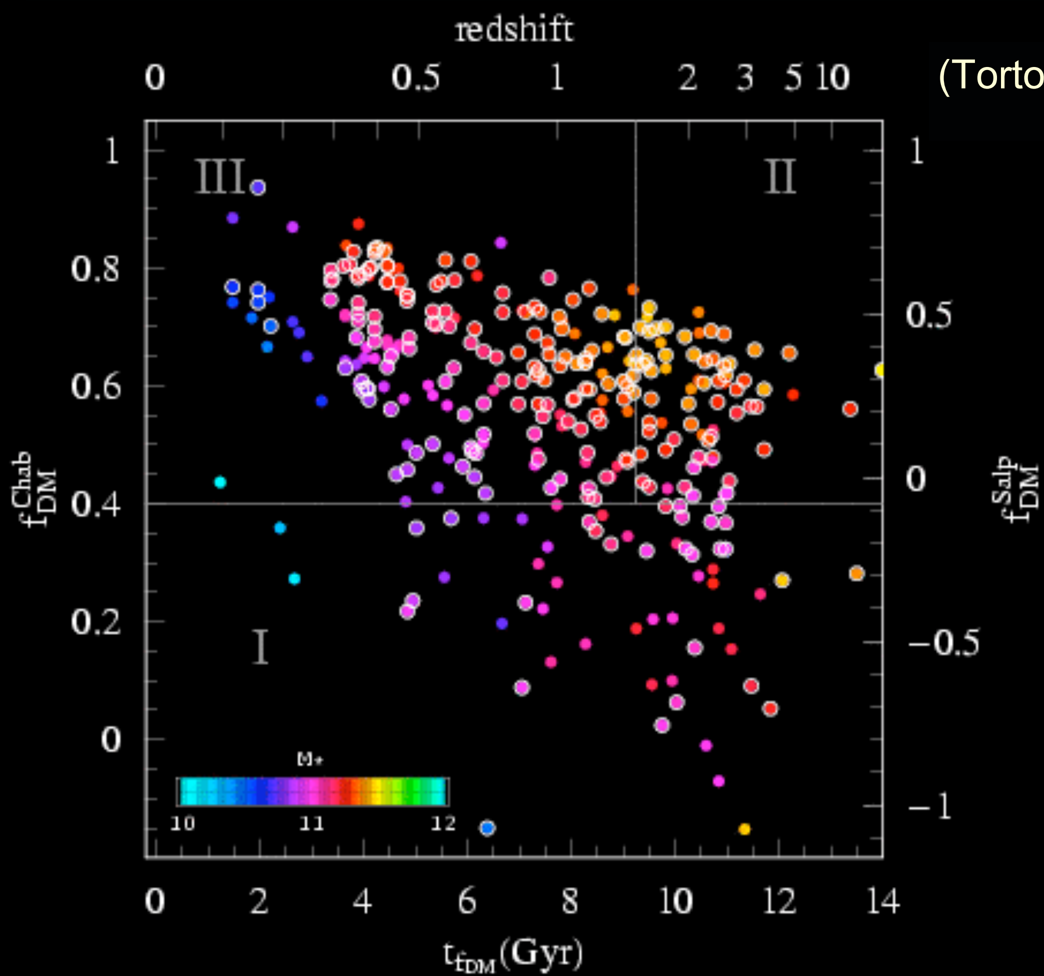


ε_{SF} maximum near L:*

- lower mass galaxies can't hold gas
- higher mass galaxies can't cool gas

(Dekel & Silk 1986; Cattaneo et al. 2006)

Linking dark matter and star formation



(Tortora et al. 2008 → Napolitano et al. 2009b)

f_{DM} in early-types decreases with stellar age

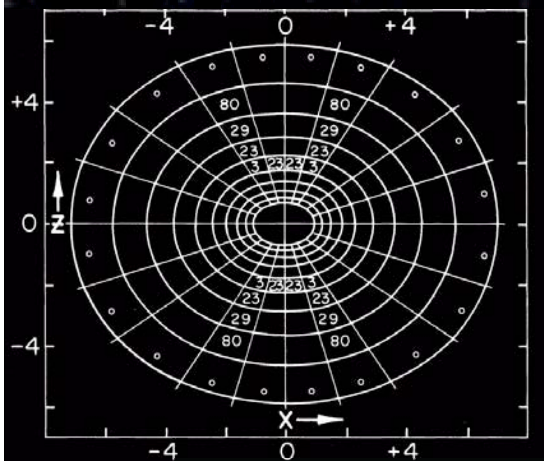
Mass assembly histories would predict *opposite* trend (more DM than stars accreted at later times)

→ ε_{SF} decreases with time

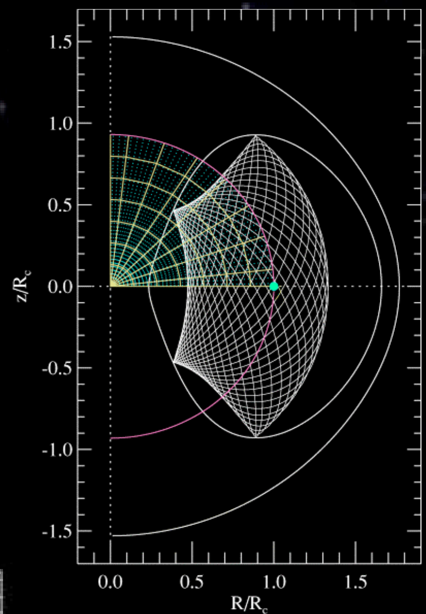
→ “DM upsizing”

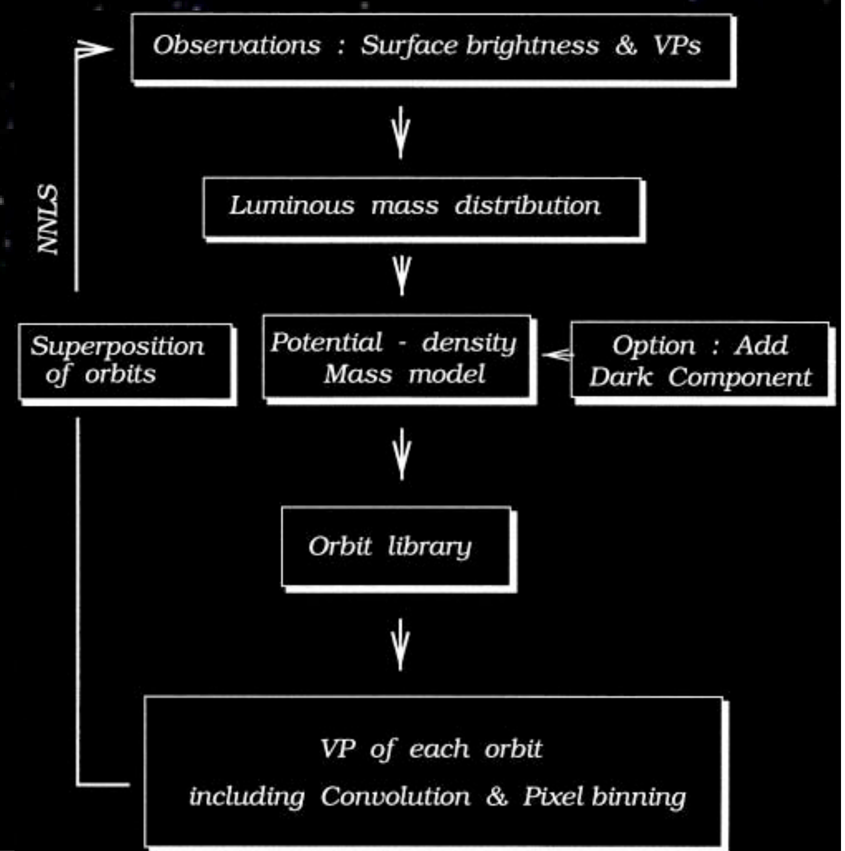
Orbit models (spherical, axisymmetric-3I, triaxial)

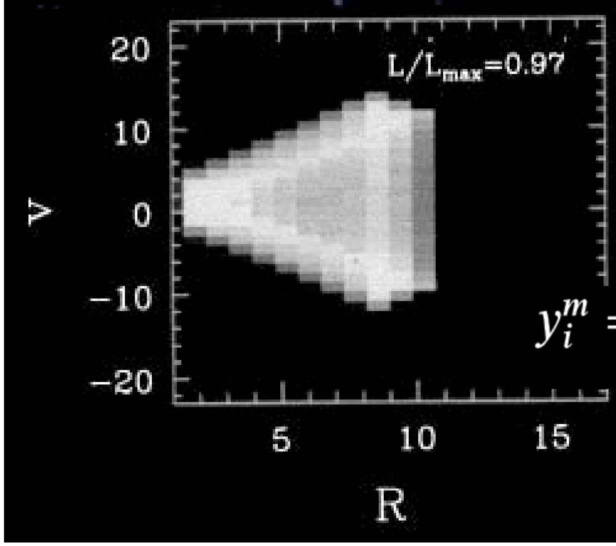
(Schwarzschild 1979; Richstone & Tremaine 1984; Rix et al. 1997; van der Marel et al. 1998; Romanowsky & Kochanek 1999, 2001; Cretton & van den Bosch 1999; Gebhardt et al. 2000; Cappellari et al. 2002, 2006; Verolme et al. 2002; Copin et al. 2004; Valluri et al. 2004; Krajnović et al. 2005; Thomas et al. 2005; van de Ven et al. 2006; Chanamé et al. 2008; van den Bosch et al. 2008; etc.)



orbit weights w_k







project to observables

$$y_i^m = \sum_k w_k^2 \langle K_{ik} \rangle_{t,\theta,\phi}$$

- physical DF (stability unknown)
- fully non-parametric DF (not Φ)
- higher-order LOSVD easy

Model fits to data

Minimize goodness-of-fit:

$$\chi^2 = \sum_i \left(\frac{y_i^{\mathrm{m}} - y_i^{\mathrm{d}}}{\Delta y_i} \right)^2$$

68% one-parameter confidence interval:

$$\Delta\chi^2 = 1$$

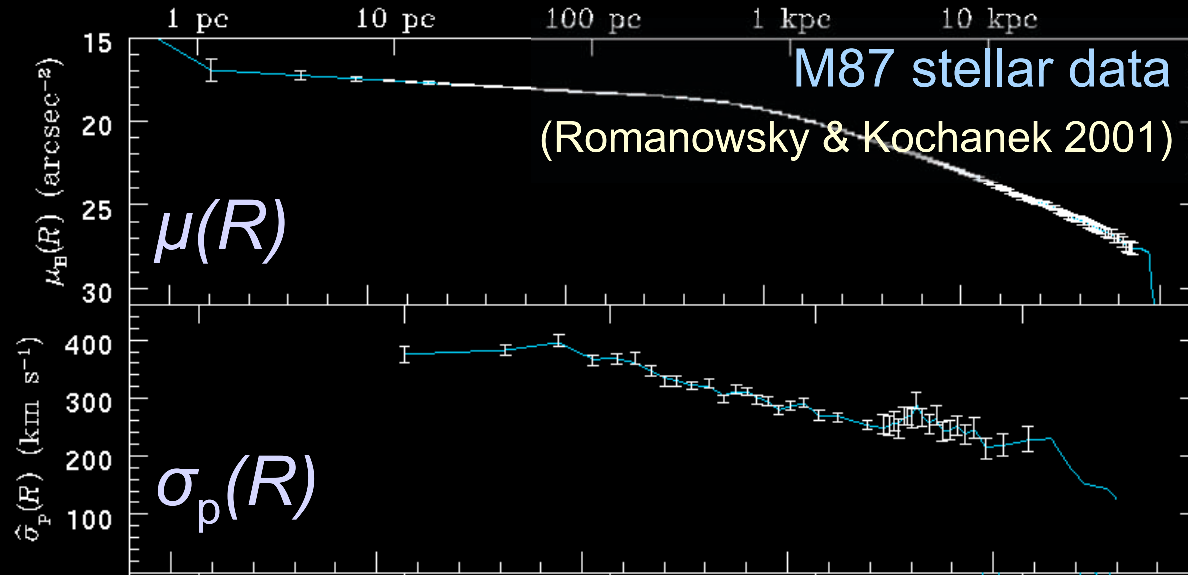
$N_{\mathrm{dof}} \equiv N_{\mathrm{data}} - N_{\mathrm{param}} < 0$?

Regularization:

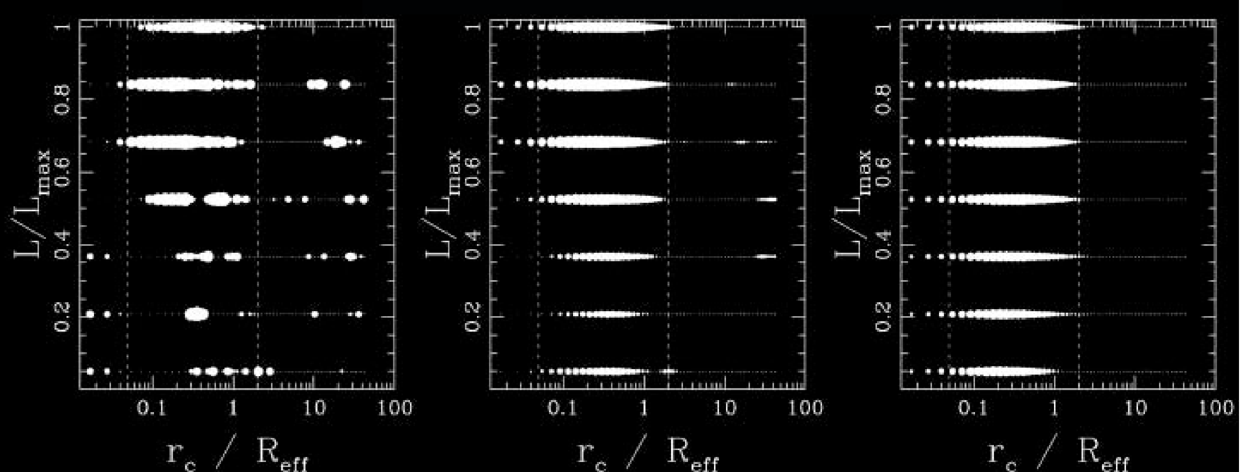
$$f(w) \equiv \tfrac{1}{2}\chi^2 + \lambda S$$

e.g. maximum entropy:

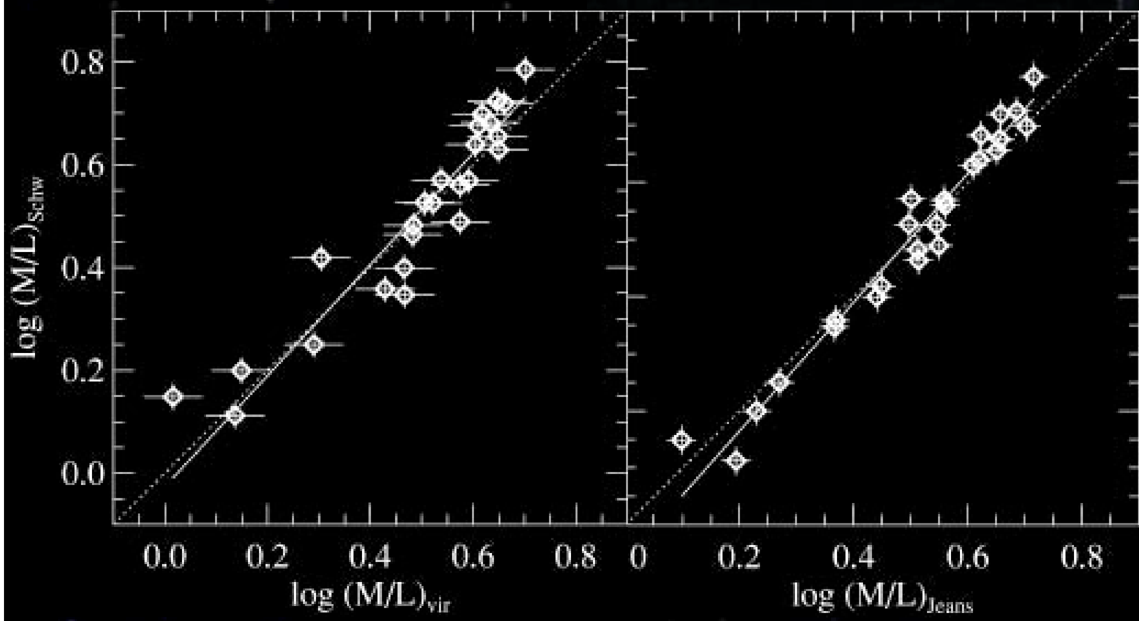
$$S = \sum_k w_k^2 \ln w_k^2$$



λ increasing $\longrightarrow$ (Rix et al. 1997)



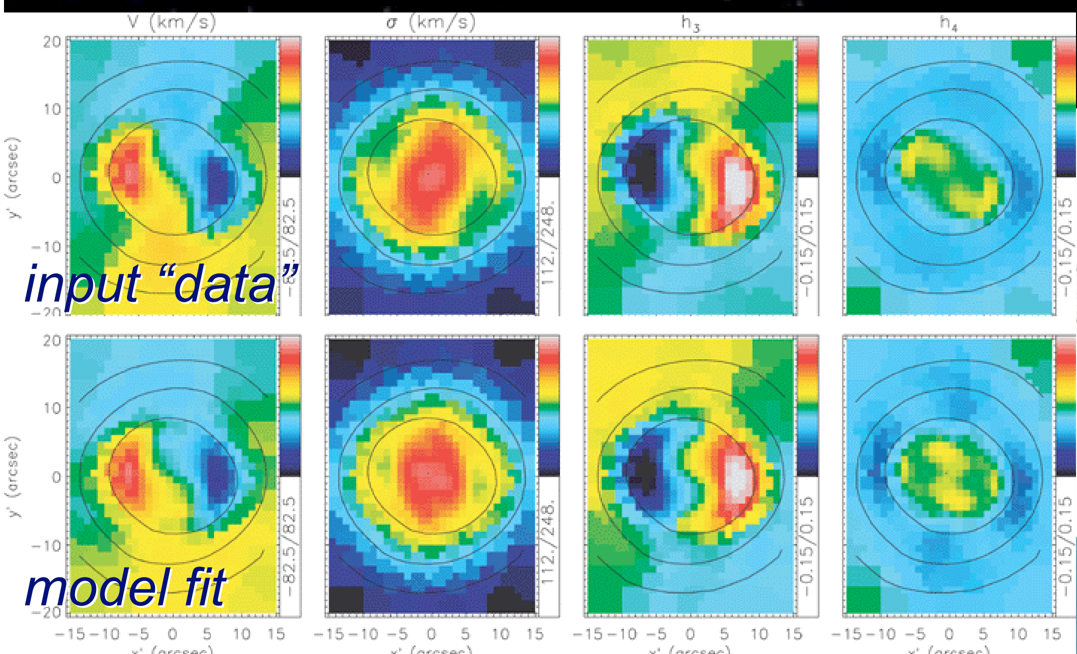
Model accuracy

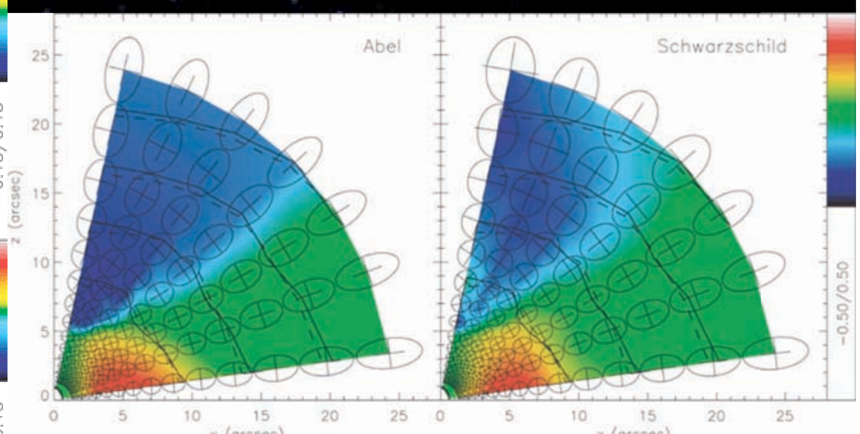


Comparing *M/L* to 3-I axisymmetric orbit models
(Cappellari et al. 2006)

- *Virial estimator* $M_* \propto R_{eff}\sigma_{eff}^2/(GL)$ *good to 11%*
- *Jeans models good to 6%*

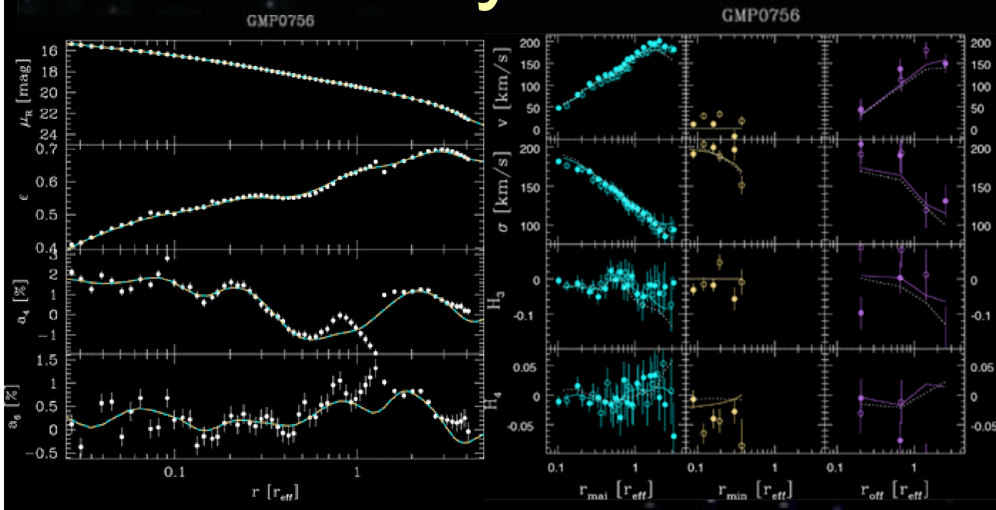
with IFU data!

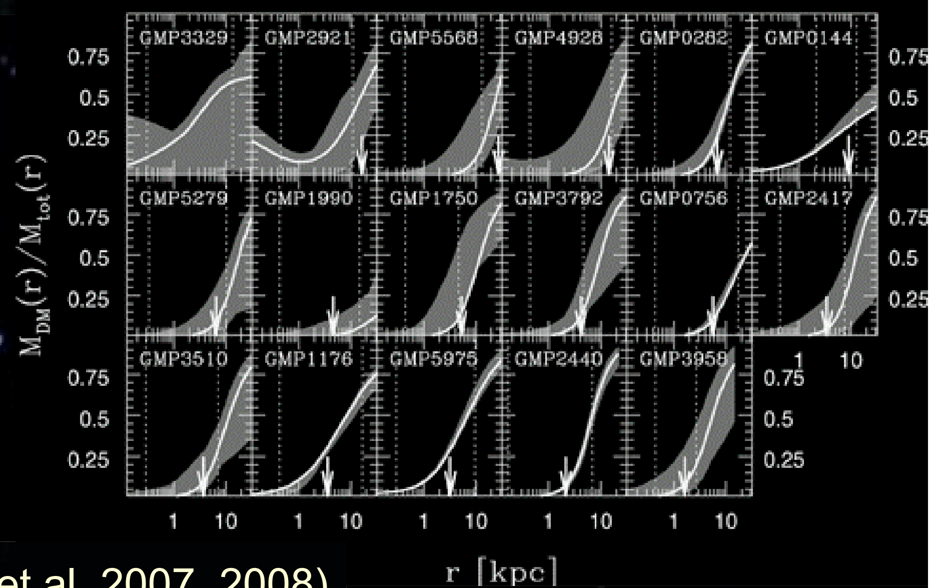




Triaxial orbit models
(van de Ven et al. 2008)

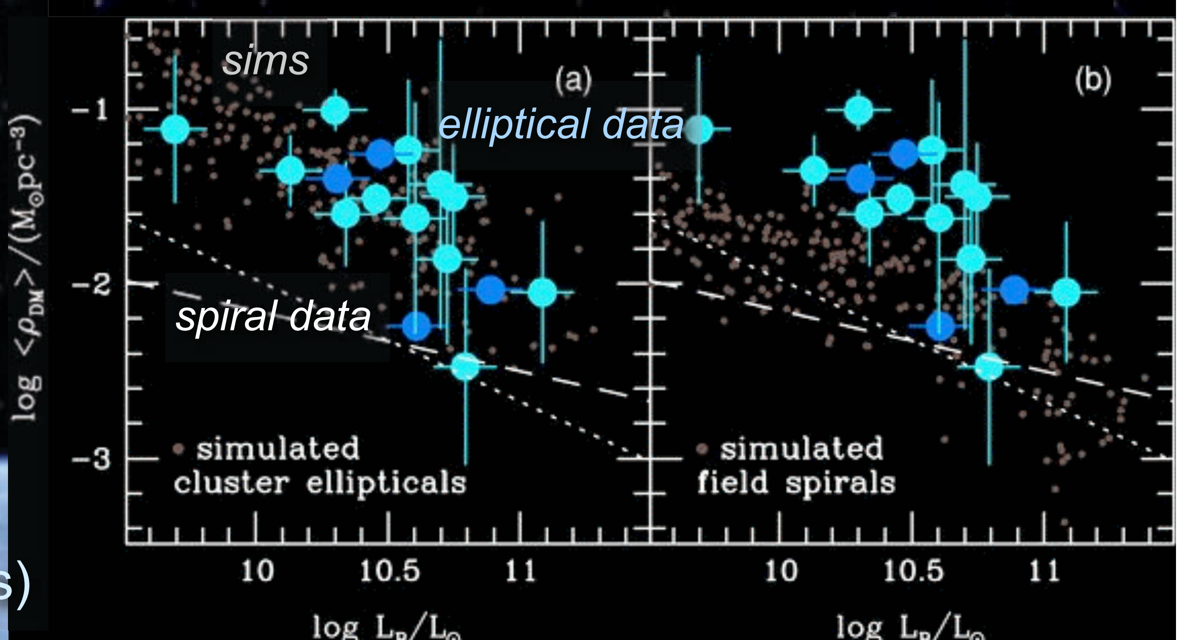
Case study: orbit models + stellar kinematics





(Thomas et al. 2007, 2008)

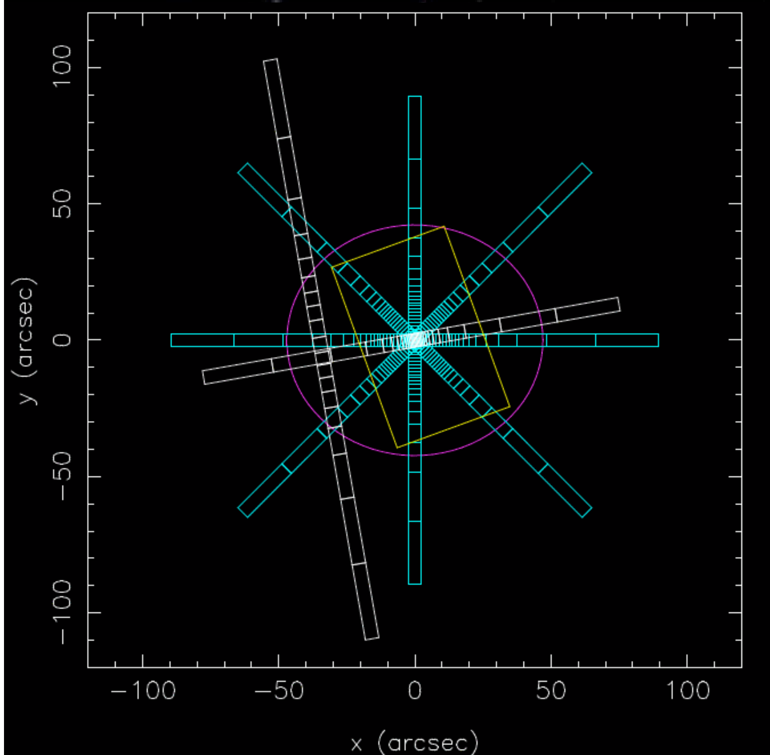
- 3I axisymmetric models of 19 early-types in Coma cluster
- Similar results to Gerhard et al. (2001)
- DM halos of early-types follow common scaling laws, ~10x denser than spirals → higher $z_{collapse}$ (~2 vs ~1)
- Halo densities ~2× higher than in Millennium Sim (σ_8=0.9) → baryonic contraction? (spirals ~2× *lower* than sims)



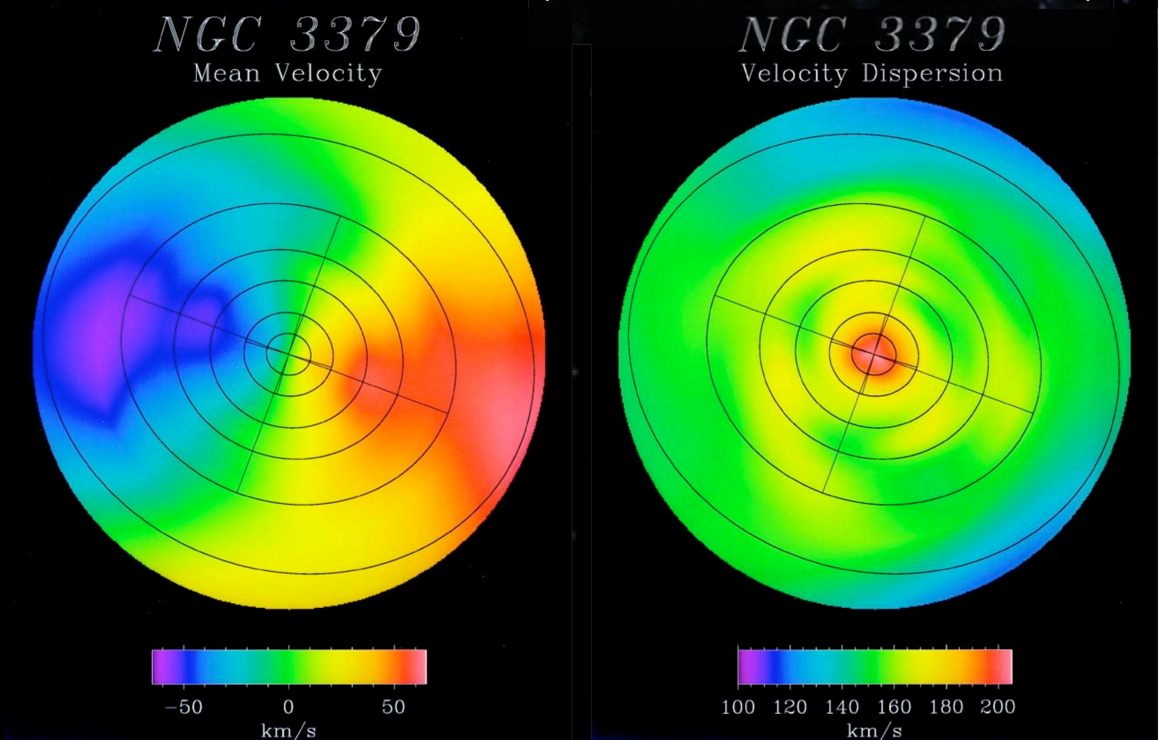
The future of stellar kinematics

Existence and properties of DM halos still at low statistical significance

Need 2-D coverage to $\gg R_{eff}$



(Statler & Smecker-Hane 1999)



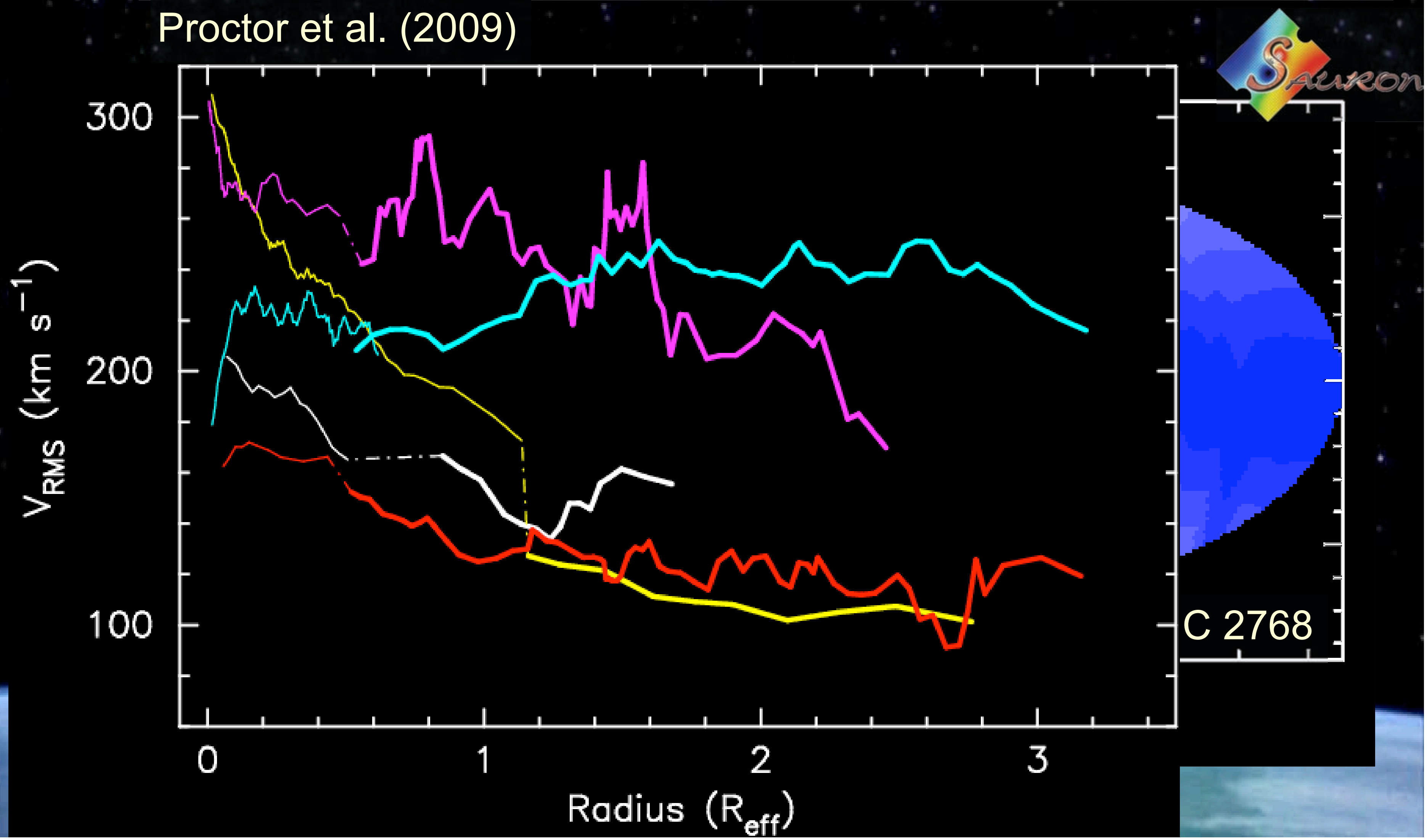
Traditional long-slit spectroscopy lacks efficiency and homogeneity

→ need new generation of wide-field IFU or new techniques

2-D stellar kinematics with Keck

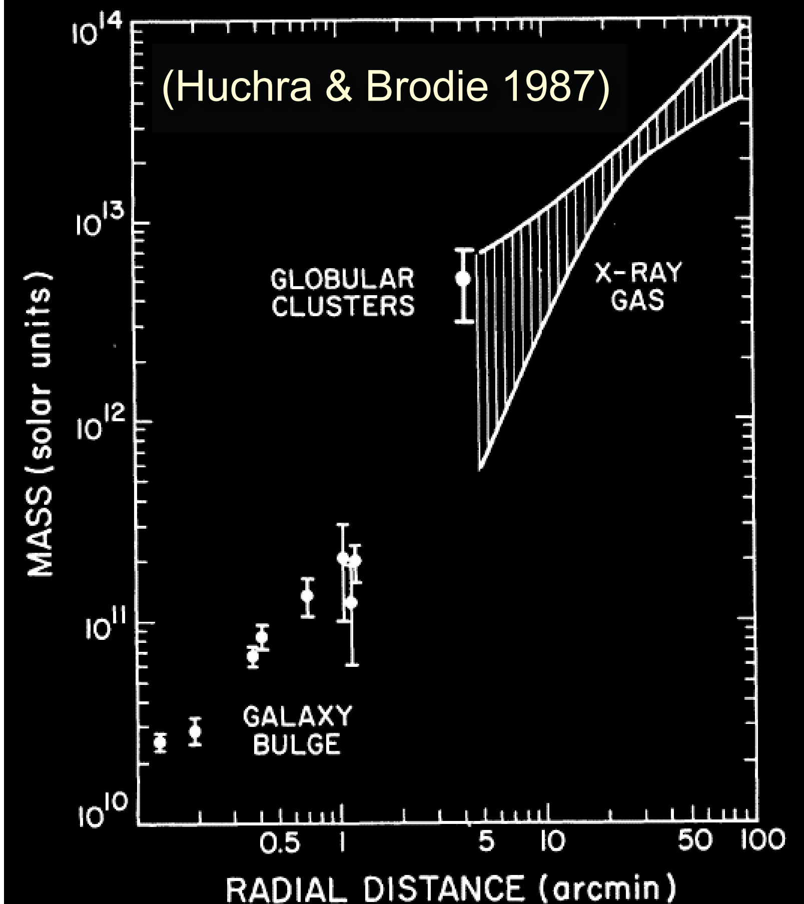
Use leftover slit light from DEIMOS GC spectra to probe galaxy kinematics to ~3 R_{eff} *(poor person's IFU)*

Proctor et al. (2009)



Globular clusters as halo mass tracers

GCs: ~10^6 stars



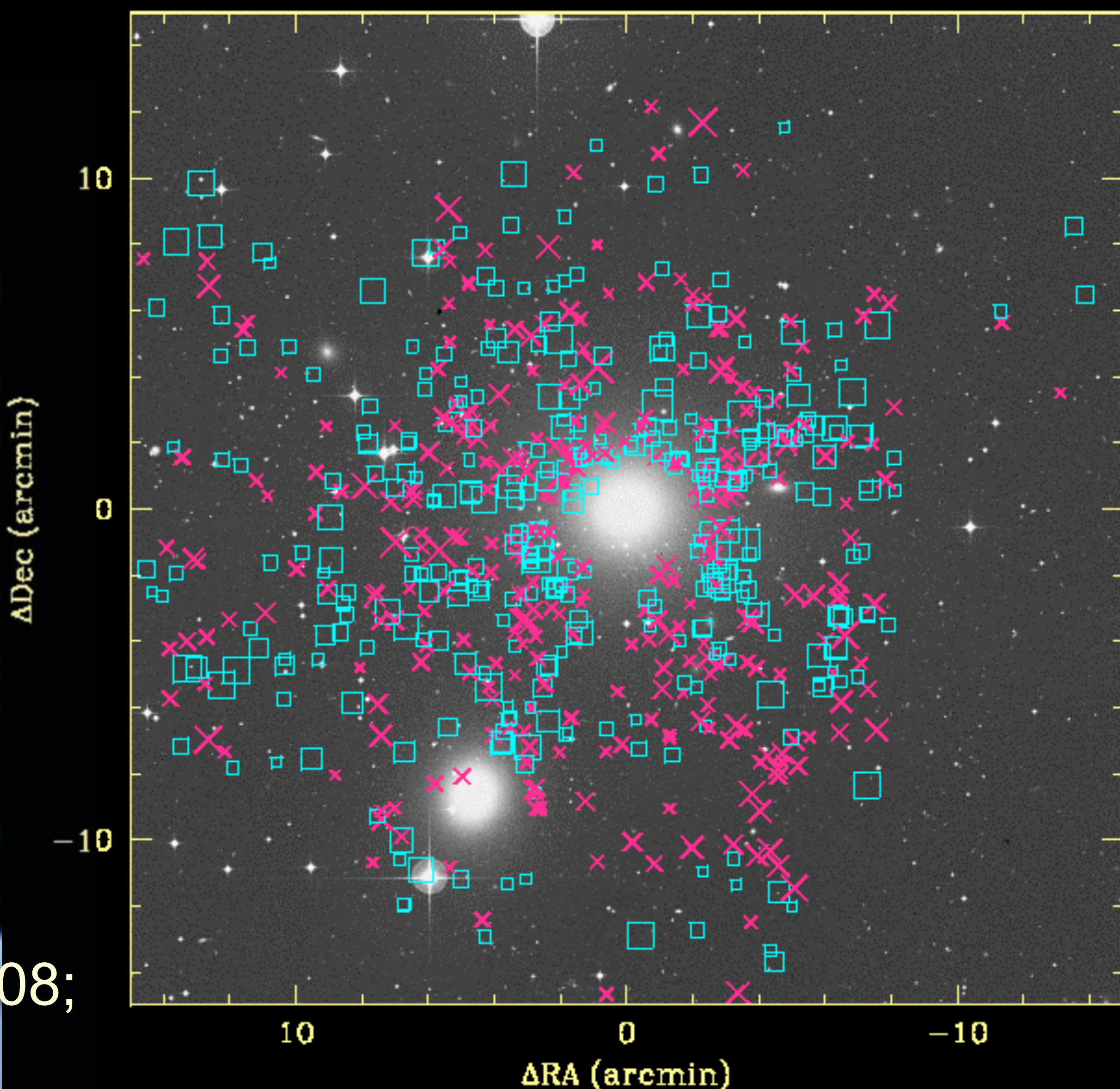
M87

Globular clusters in NGC 1399

D=19 Mpc, M_B=-21.1

Fornax central E1

VLT+FORS2/MXU,
Gemini-S+GMOS:
656 velocities
to 80 kpc
(largest data set in any galaxy)
Δv = 20-100 km/s
(Richtler et al. 2004, 2008; Schuberth et al. 2009)



SAGES Legacy Unifying Globulars and Galaxies Survey

SAGES

NSF

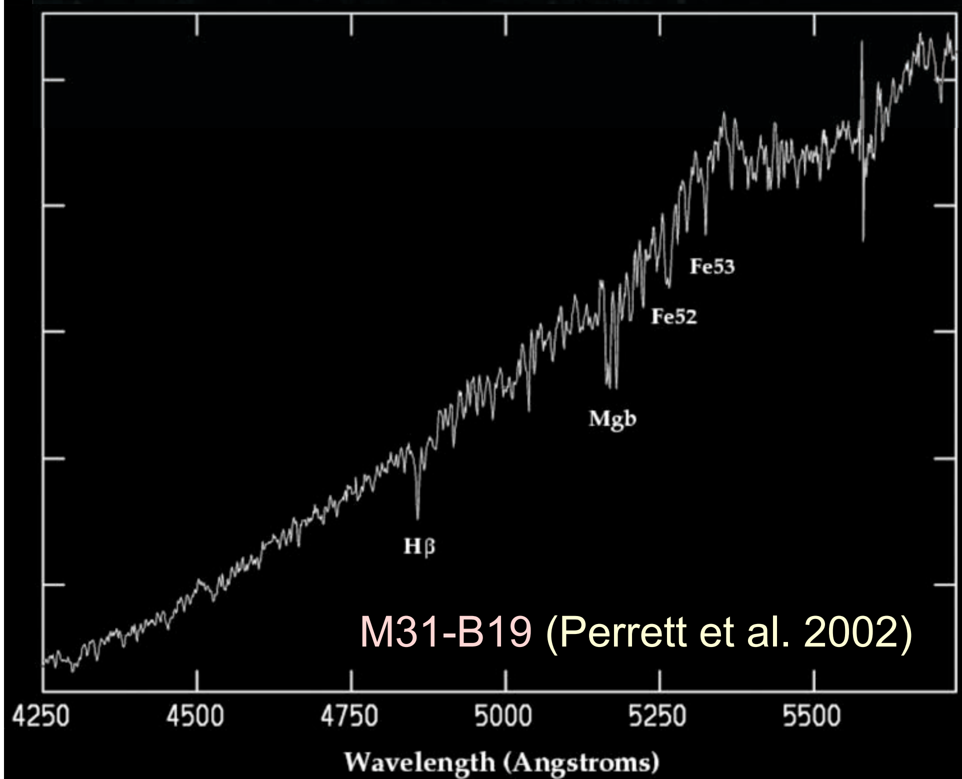
- NSF funded (2008-2010)
- 25 representative early-type galaxies:
  - spread of luminosities, environments, photometric and kinematical properties
- Global properties, with focus on halo tracers:
  - field stars, planetary nebulae, globular clusters
  - photometry, kinematics, metallicities
  - Subaru/Suprime-Cam, Keck/DEIMOS

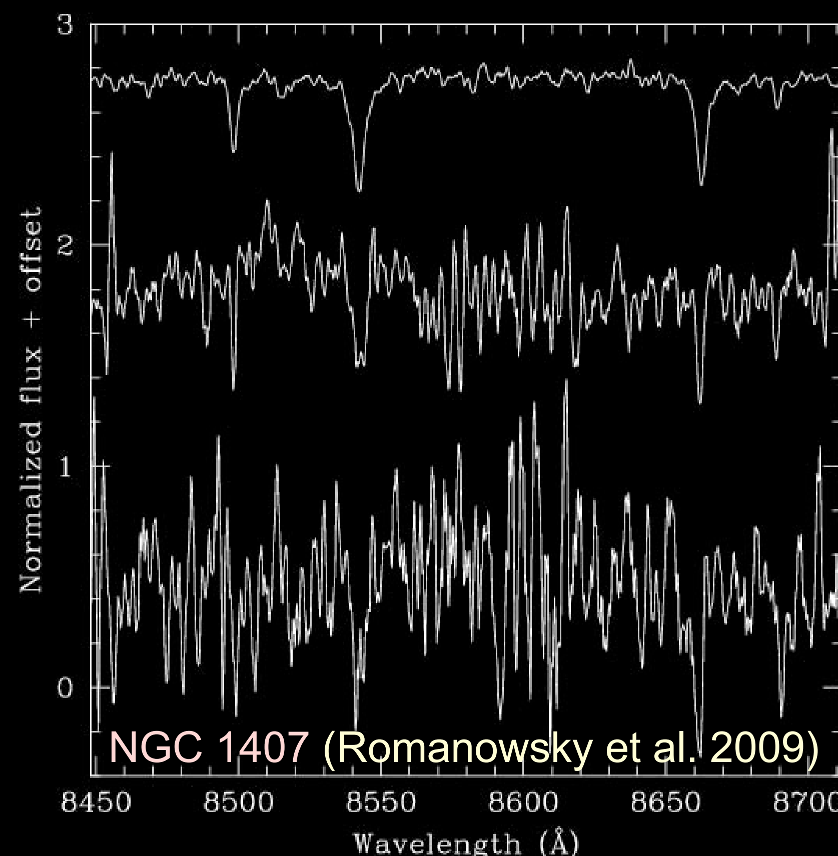
    (high-quality, deep wide-field imaging + spectroscopy)

SUBARU National Astronomical Observatory of Japan

SLUGGS

Extragalactic GC spectra for kinematics





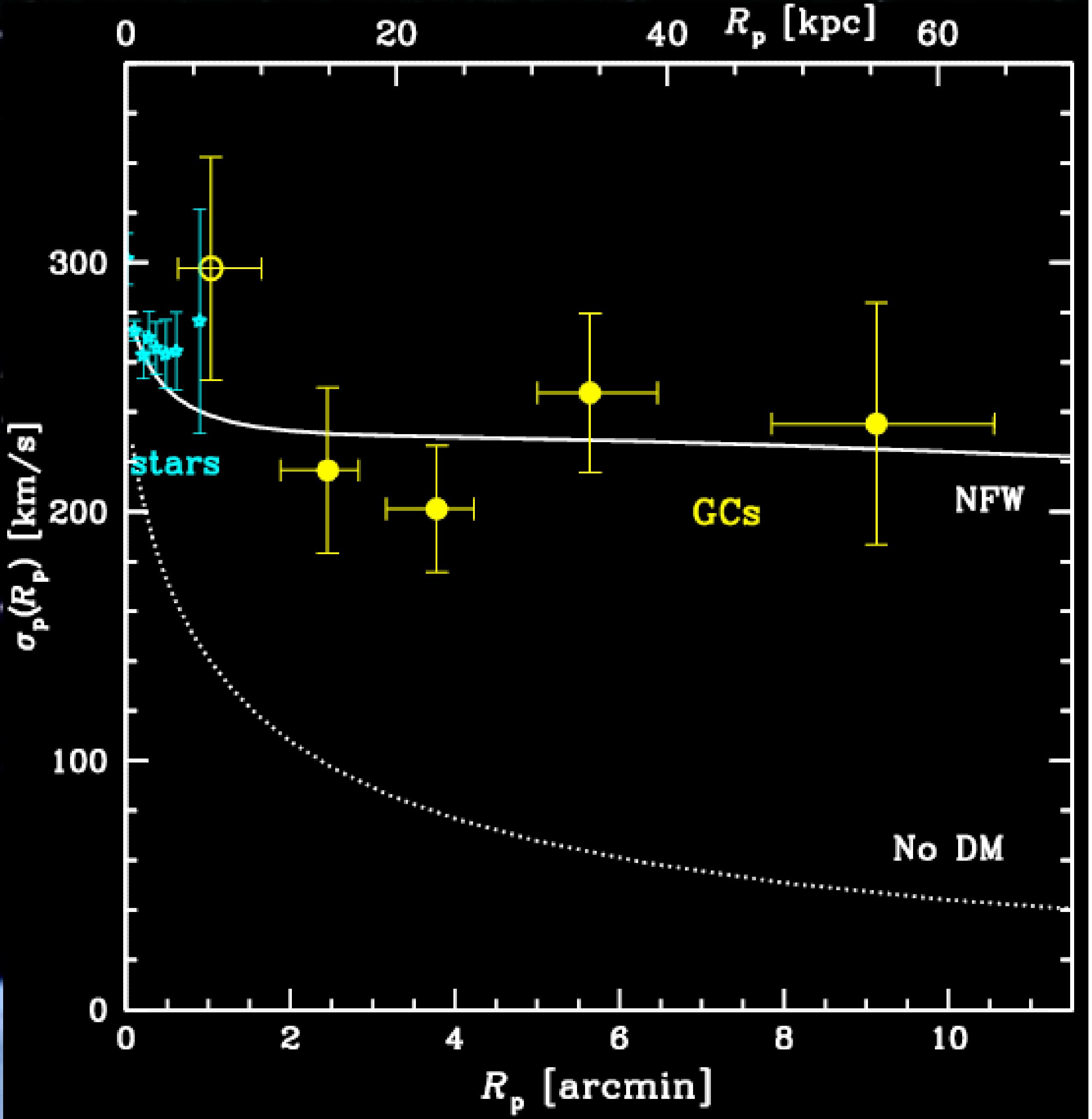
Typical wavelength range 4800-5400 Å (Keck/LRIS, VLT/FORS2, Gemini/GMOS, etc.)

NIR Ca II triplet: highly efficient with Keck/DEIMOS

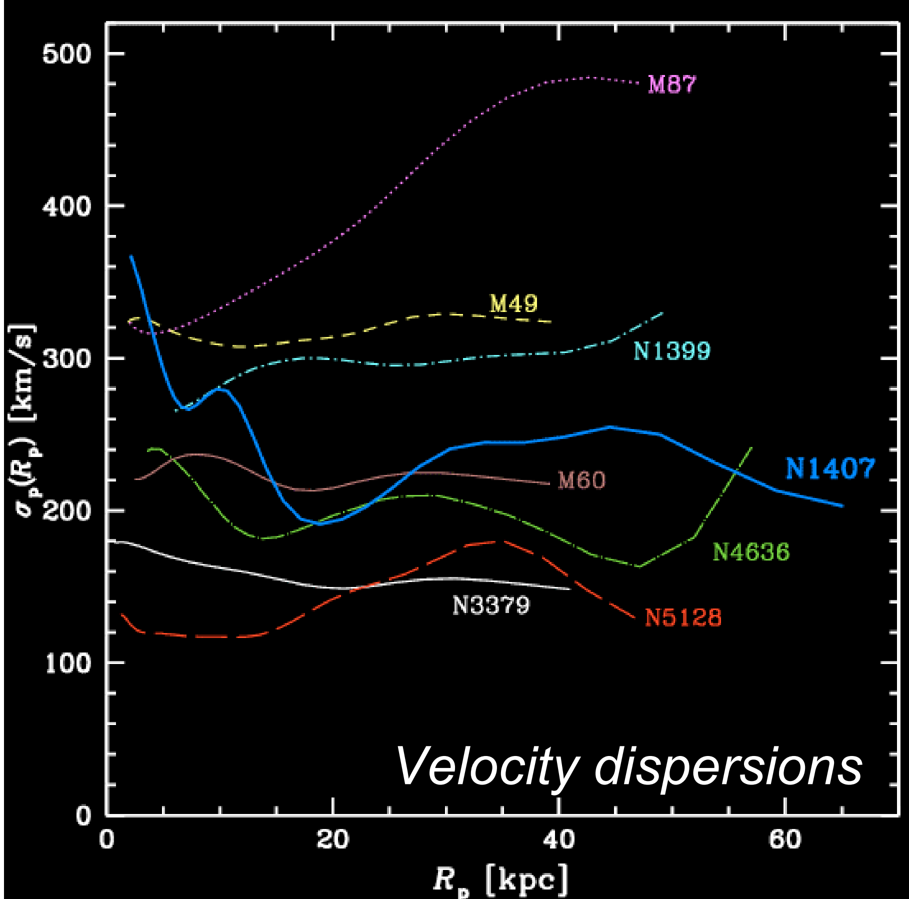
GC dynamics in NGC 1407

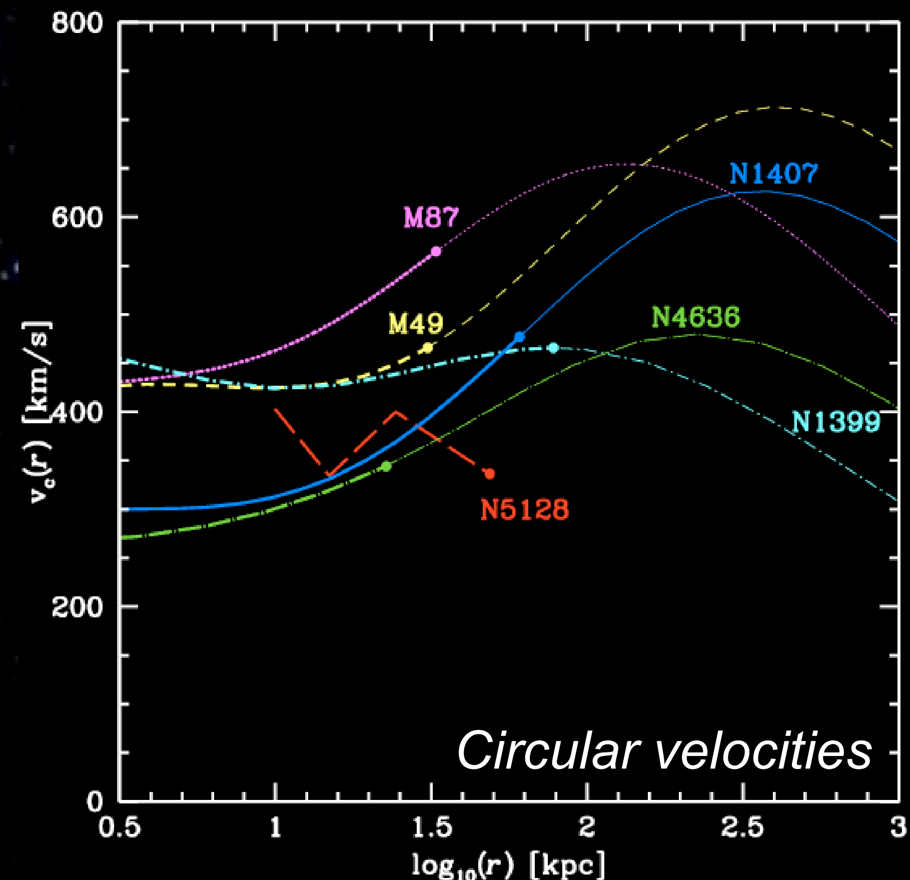
E1, M_B = -21.0,
Group central galaxy (GCG),
D = 21 Mpc

172 GC velocities from LRIS, DEIMOS *to 60 kpc (10 R_{eff})*
(Cenarro et al. 2007; Romanowsky et al. 2009)
+ ~150 new velocities to be analyzed…



GC dynamics of group-central Es





Fairly flat dispersions out to very large radii imply increasing circular velocities and group-scale DM halos

(Romanowsky & Kochanek 2001; Côté et al. 2003; Schuberth et al. 2006; Bergond et al. 2006; Woodley et al. 2007; Richtler et al. 2008; Hwang et al. 2008; Romanowsky et al. 2009)

Modeling discrete velocities

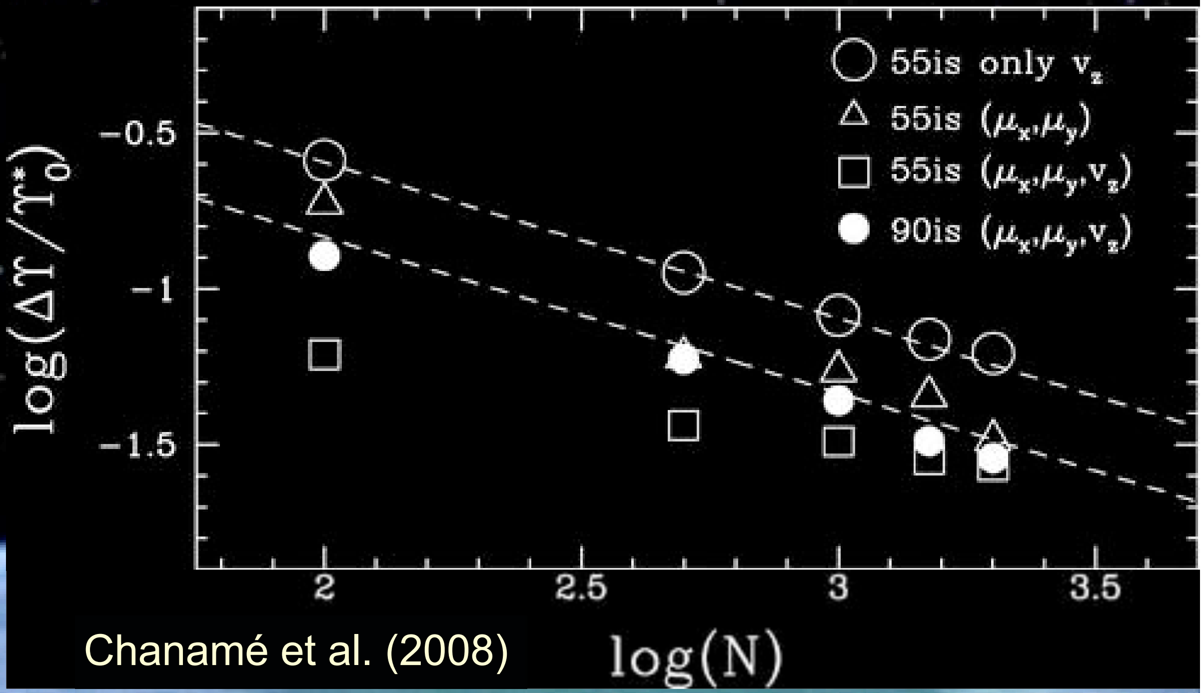
Binning (in *R*,*v*) ***loses information***

Likelihood fcn

$$\mathcal{L}_i(v_i, R_i|\mathbf{w}) \propto \int_{-\infty}^{\infty} \frac{dL}{dv_{\rm p}}(v_{\rm p}, R_i) e^{-(v_i - v_{\rm p})^2/2(\Delta v_i)^2} dv_{\rm p}$$

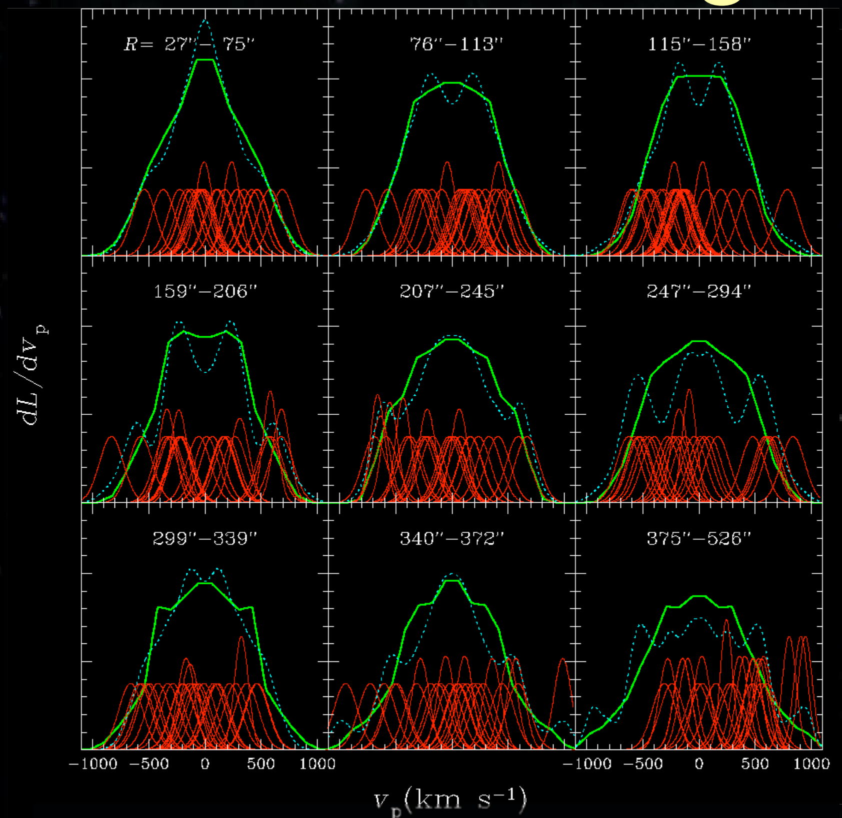
$$\chi^2 = -2\ln\mathcal{L}$$

~1000 velocities needed to break mass-anisotropy degeneracy in axisymmetric const-*M/L* system



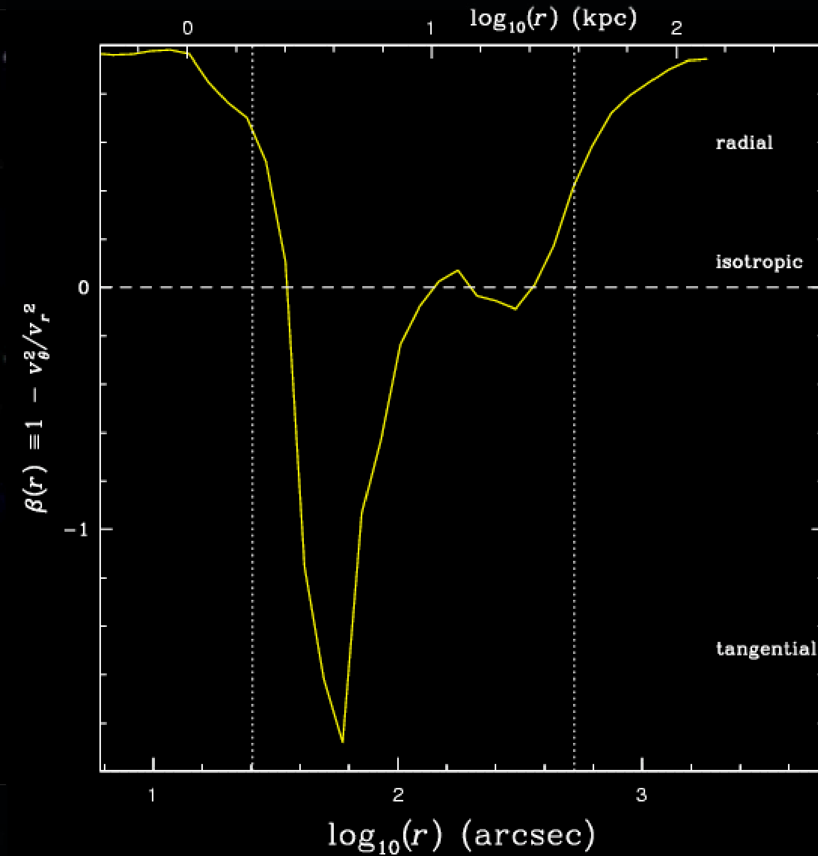
Chanamé et al. (2008)

Orbit modeling with discrete velocities



Schwarzschild orbit model fit of stellar + GC kinematics in M87
(Romanowsky & Kochanek 2001)

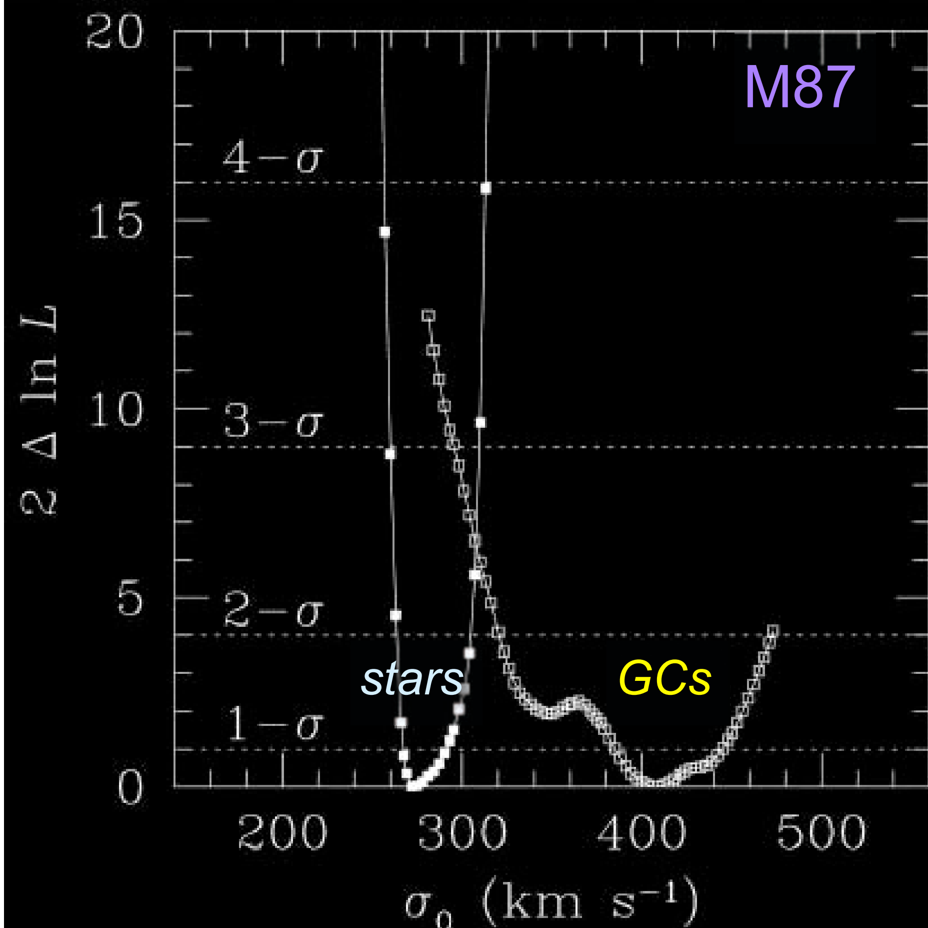
Unbinned LOSVD fitting, shown in radial bins:
- **model**
- **data**
- **simulated from data**

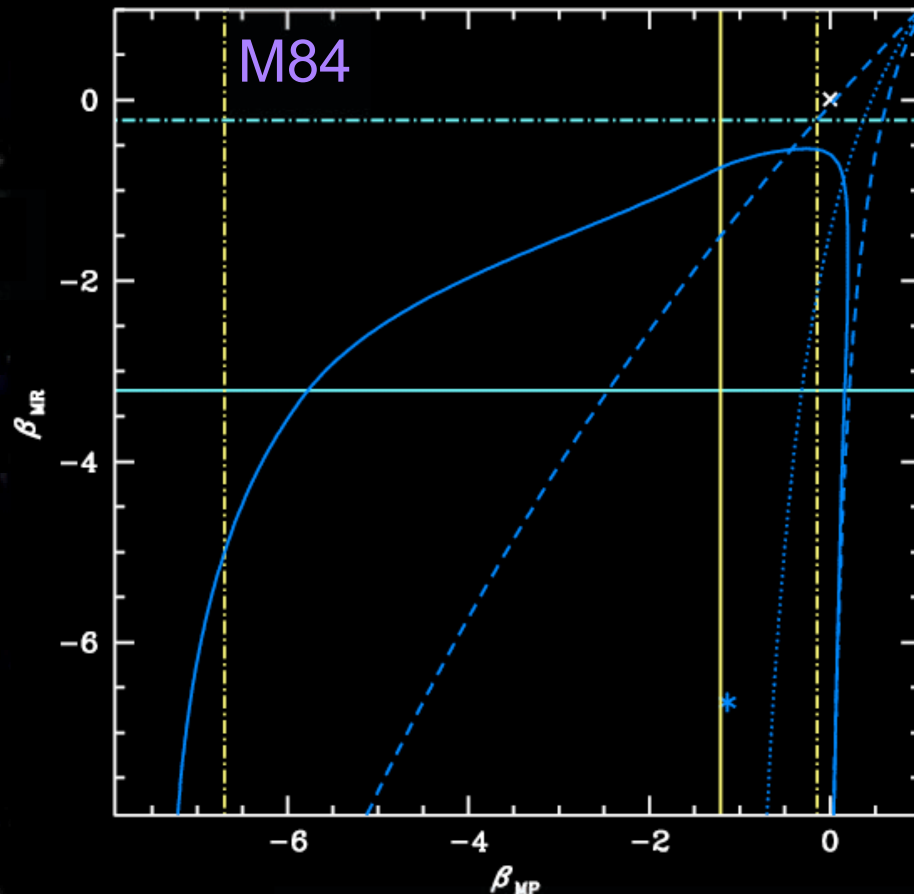


GCS roughly isotropic overall, possibly tangential toward center

cf. Côté et al. (2001); Wu & Tremaine (2006)

More breaks in the mass-anisotropy degeneracy

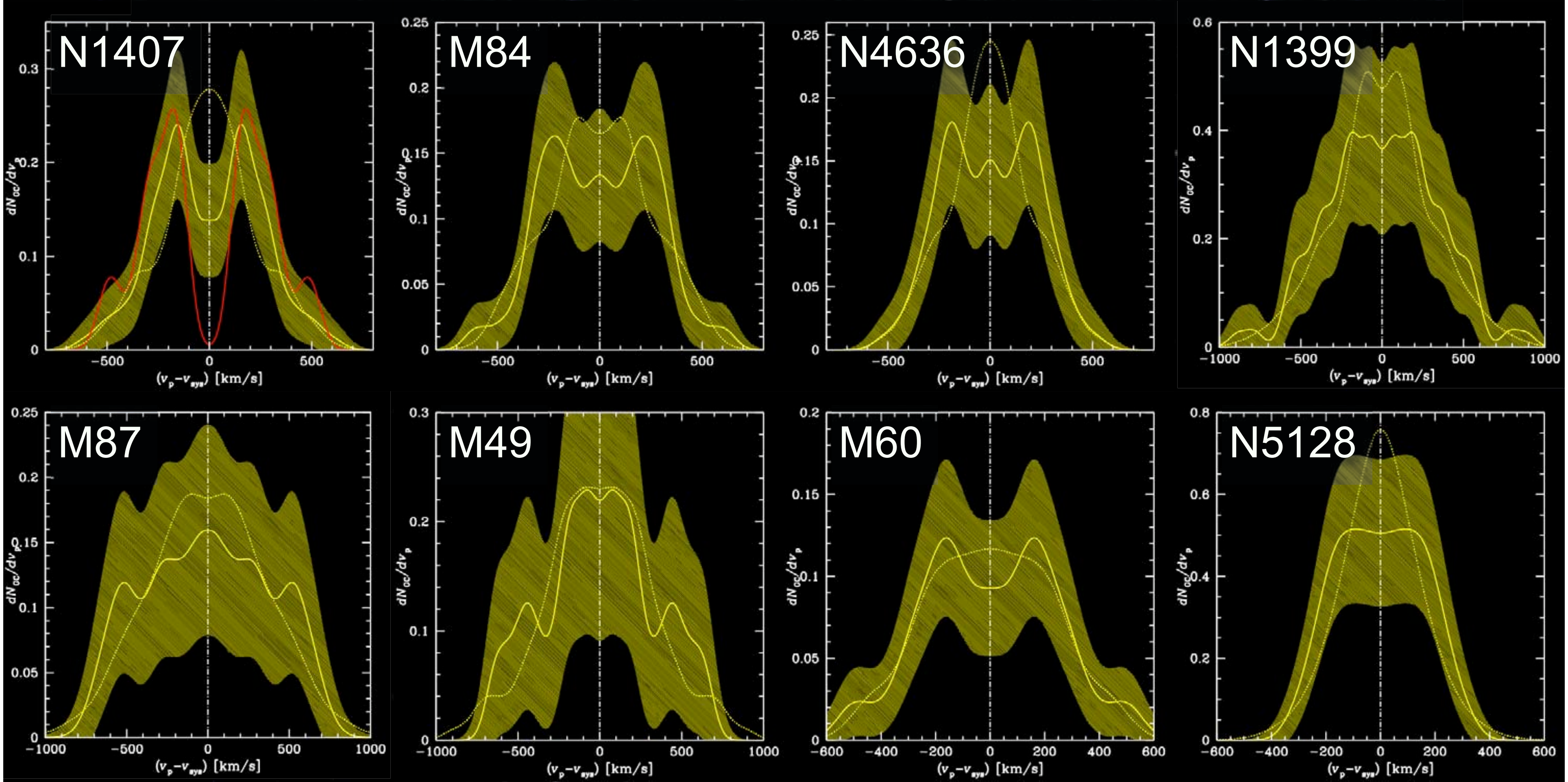




Stars or GCs alone do not rule out ρ(r)~ r $^{-2}$
but used jointly they do…
→ multiple independent mass tracers!

Metal-poor and metal-rich GC subsystems require consistent solution
(Kumar et al. in prep)

Dynamical uniformity of tracers



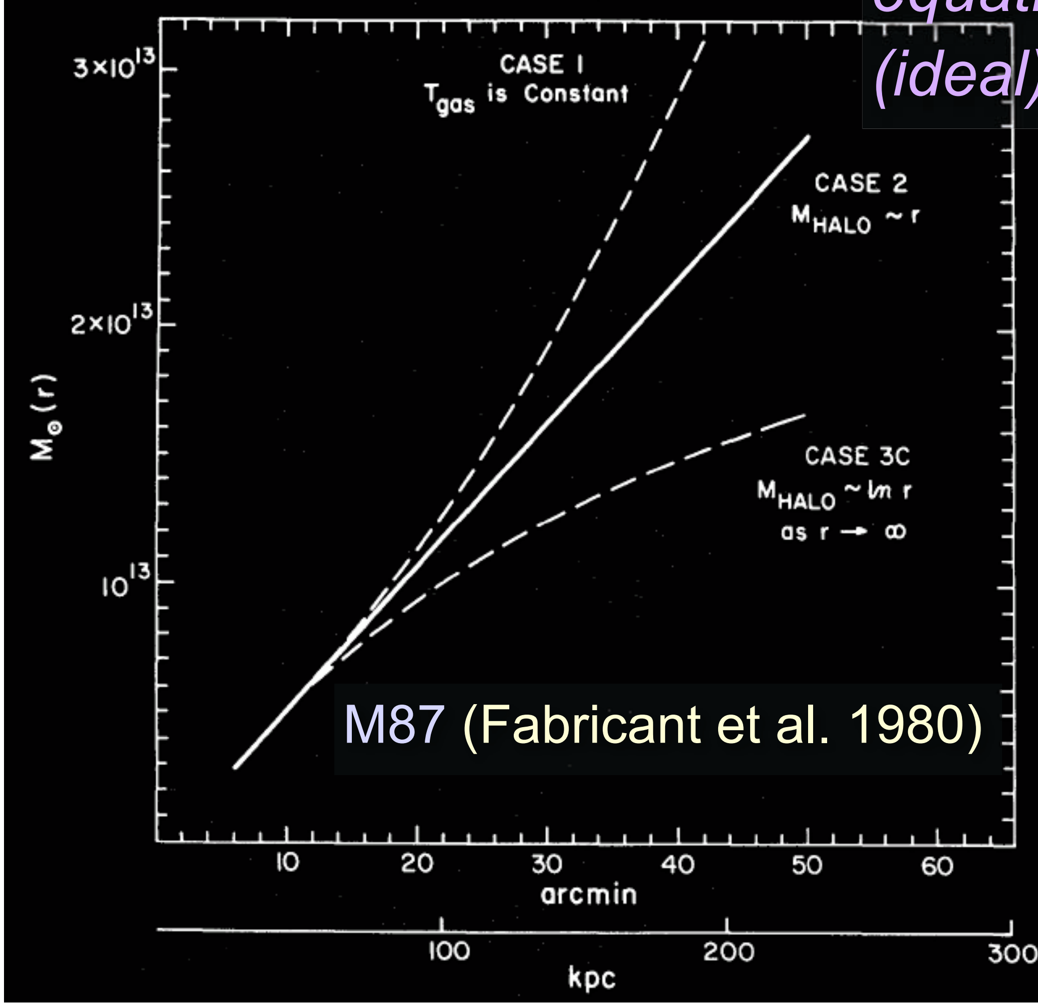
- *Bright GCs show flat-tops / double-peaks in almost all cases!* (significant in ~3 cases)
  - ➢ DF changes with luminosity: $\nu(r)$ from faint GCs may not be valid

(Romanowsky et al., in prep.)

Mass in early-types: X-ray gas

$$v_c^2(r) = -\frac{k_B T_X(r)}{\mu m_p}\left(\frac{d\ \ln\ n_g}{d\ \ln\ r} + \frac{d\ \ln\ T_X}{d\ \ln\ r}\right)$$

equation of hydrostatic equilibrium: (ideal) gas pressure balances gravity



M87 (Fabricant et al. 1980)

n_g: gas density

T_X: gas temperature

(~10^7 K, 1 keV)

(Fabricant et al. 1980)

thermalized hot gas fills halo potential well and emits X-rays

Mass cross-checks: GCs + X-rays in NGC 1407

***Chandra*/ACIS-S3, 49 ksec**

Deproject temperature in coarse radial bins, density in fine bins

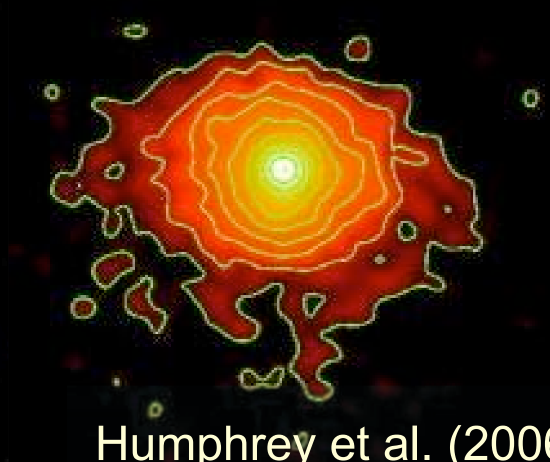
Model unresolved point-sources as power-law component

Hydrostatic equilibrium equation:

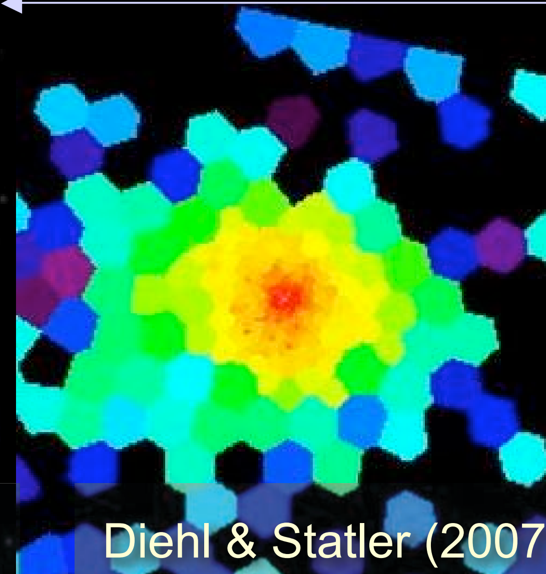
$$v_c^2(r) = -\frac{k_B T_X(r)}{\mu m_p} \times \left(\frac{d\ \ln\ \rho}{d\ \ln\ r} + \frac{d\ \ln\ T_X}{d\ \ln\ r} \right)$$

(Romanowsky et al. 2009; Johnson et al. 2009)

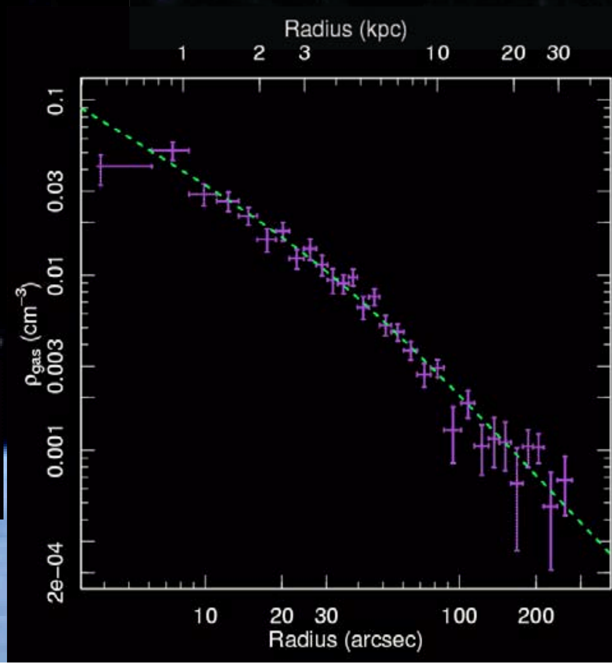
5′ = 30 kpc

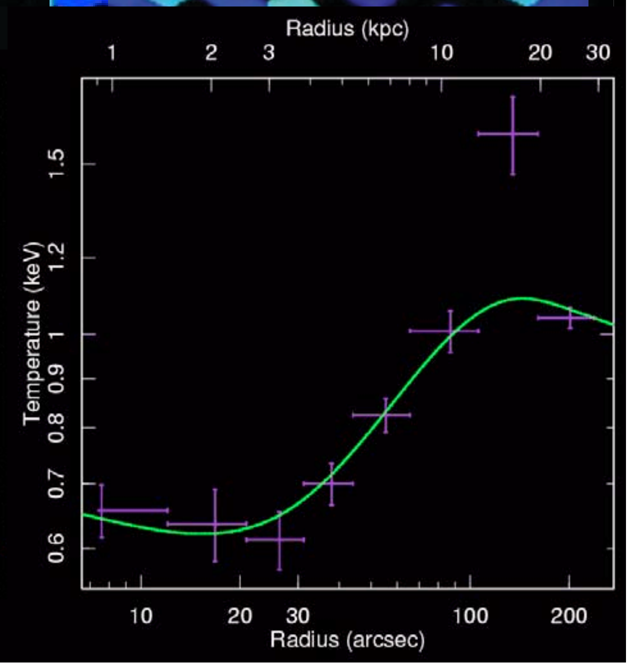


Humphrey et al. (2006)



Diehl & Statler (2007)



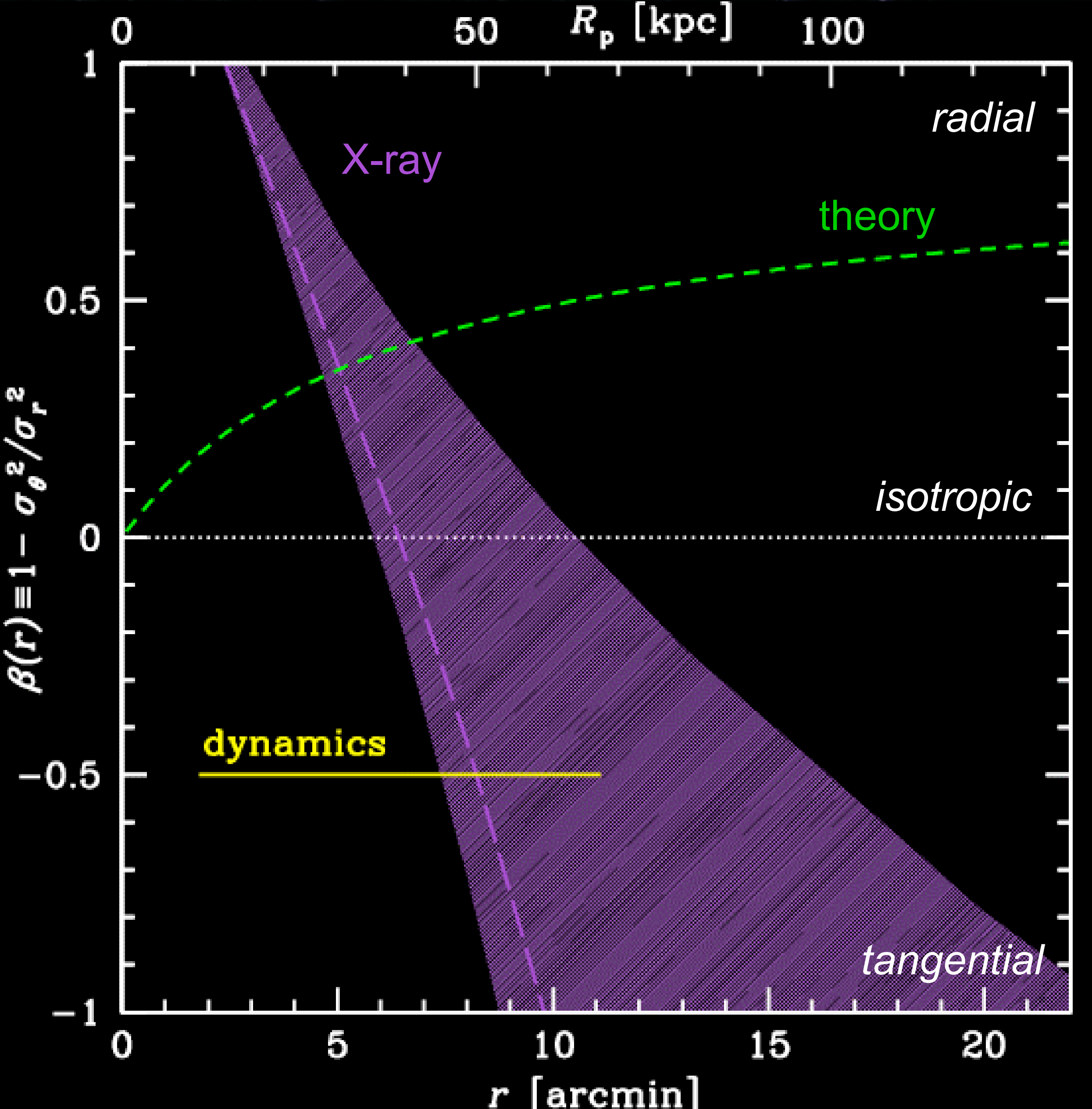


NGC 1407 mass profile: X-rays vs GCs

GC kinematics from DEIMOS, X-ray mass from *Chandra*

discrepant at 2 σ
(cf. high-c_{vir}, low Υ_* found by Humphrey et al. 2006)

What β(r) for GCs required for consistency?



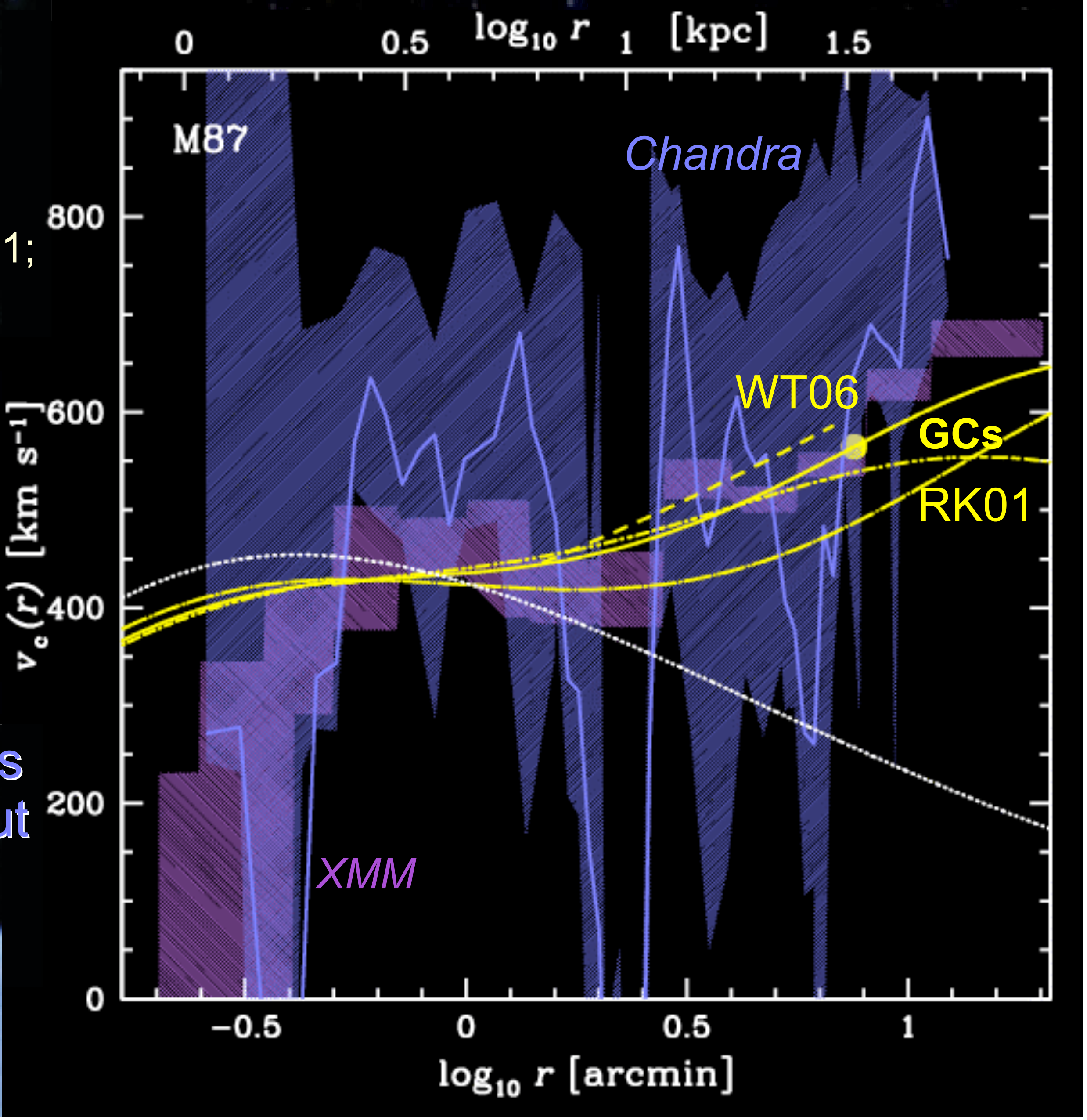
Cross-check: X-rays & dynamics in M87

Orbit modeling
of stars + 234 GCs with
non-parametric *β(r)*
(Cohen & Ryzhov 1997;
Romanowsky & Kochanek 2001;
Wu & Tremaine 2006)

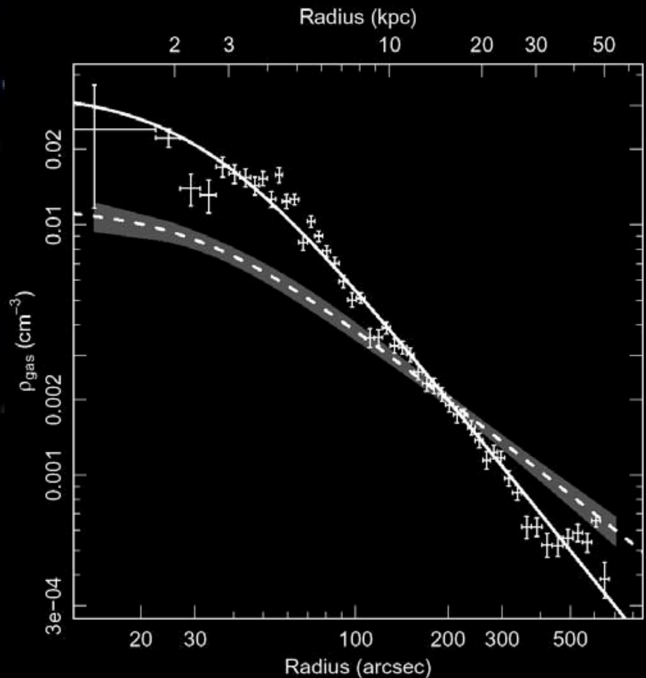
XMM-Newton
(Matsushita et al. 2002)

⇒ *good agreement except inside 2 kpc*

Chandra: unphysical mass wiggles from shocks(?) but broad agreement
(Churazov et al. 2008)

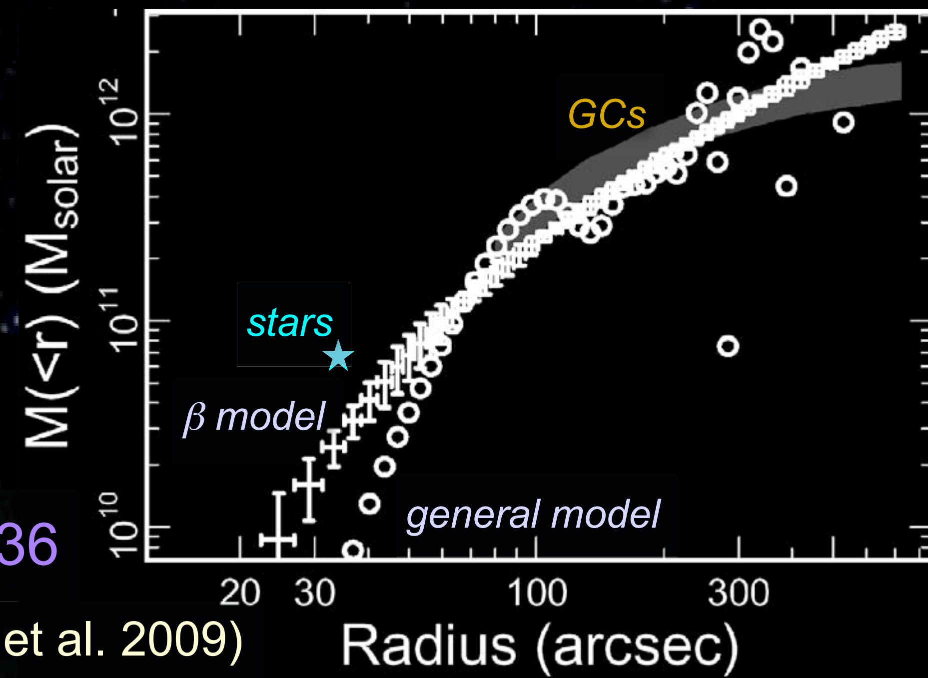


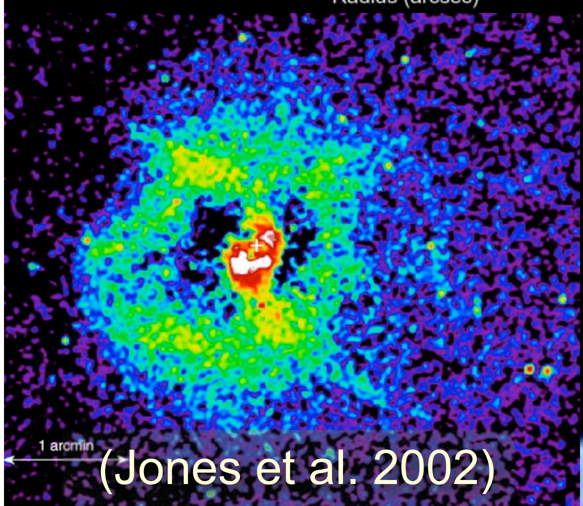
More X-ray/GC cross checks



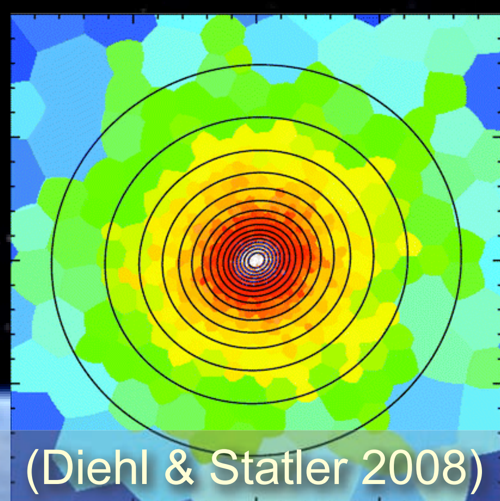
NGC 4636

(Johnson et al. 2009)

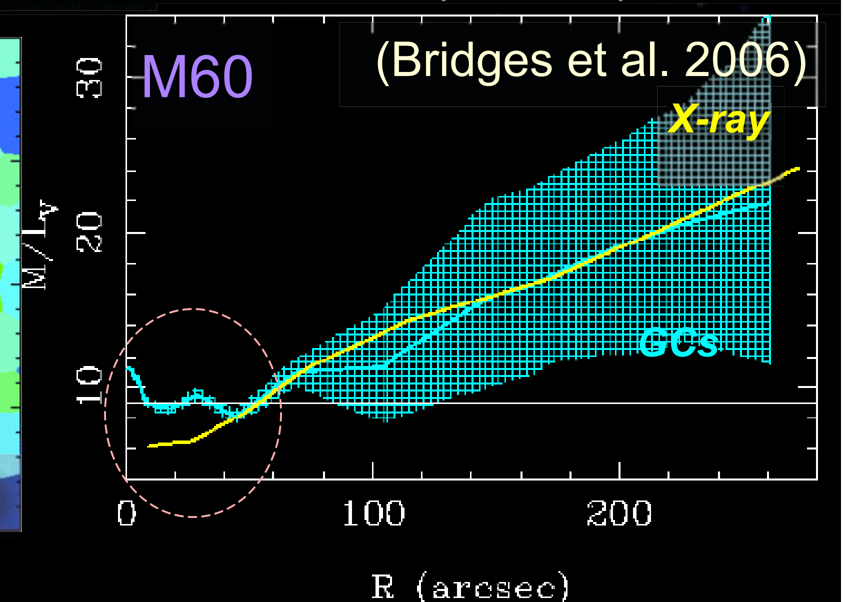




(Jones et al. 2002)



(Diehl & Statler 2008)



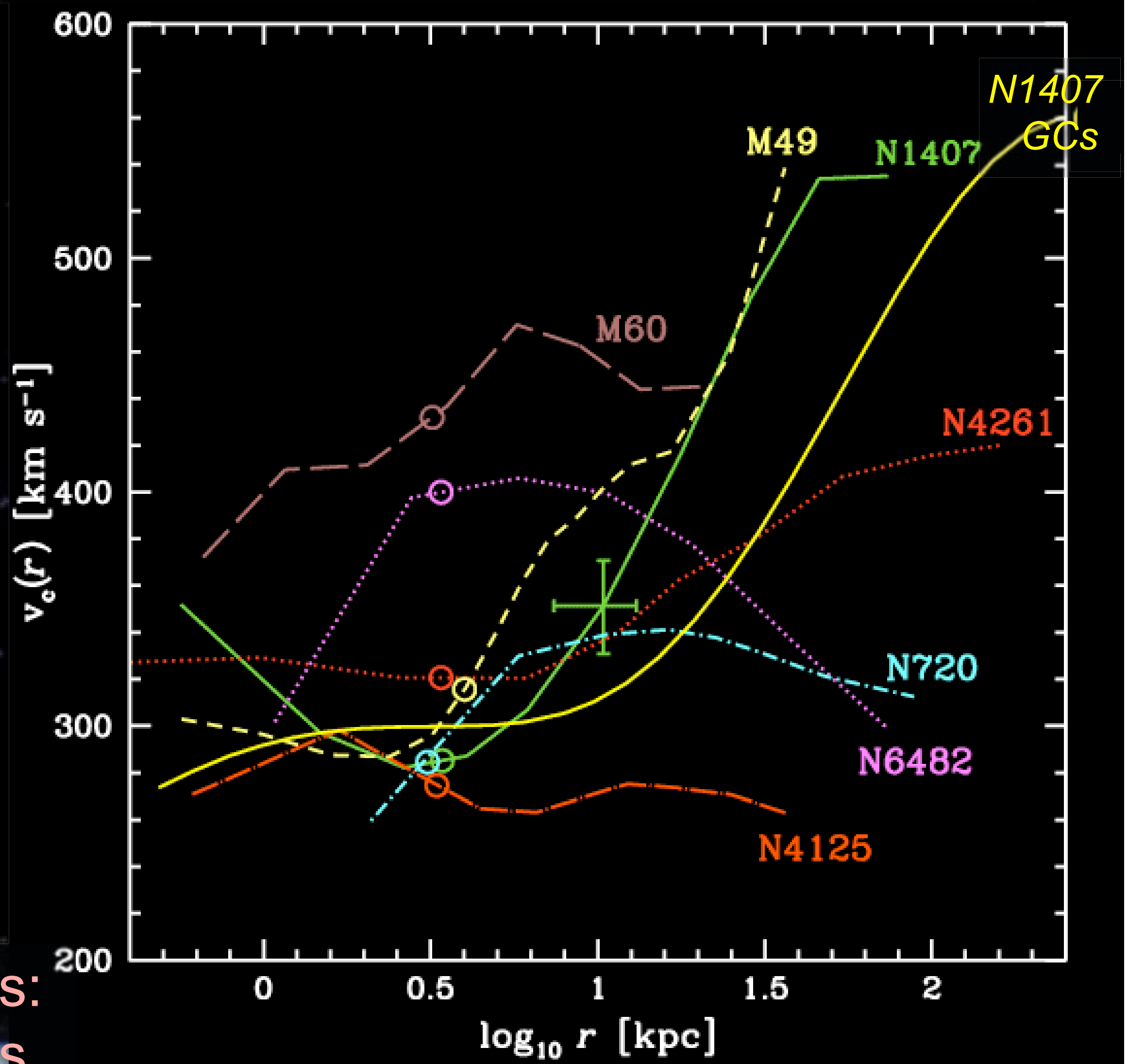
X-ray masses of galaxies/groups

Chandra study implies extensive DM halos
(Humphrey et al. 2006)

"shoulders" seen in mass profiles (e.g. Zhang et al. 2007)
→ *lack of hydrostatic equilibrium?*

ΛCDM halo fits to X-ray data require:
- low stellar *M/L* **and**
- high halo concentrations

(indirect inconsistency)



A few dynamics cross-checks:
X-ray mass too low in centers
non-thermal pressure support?

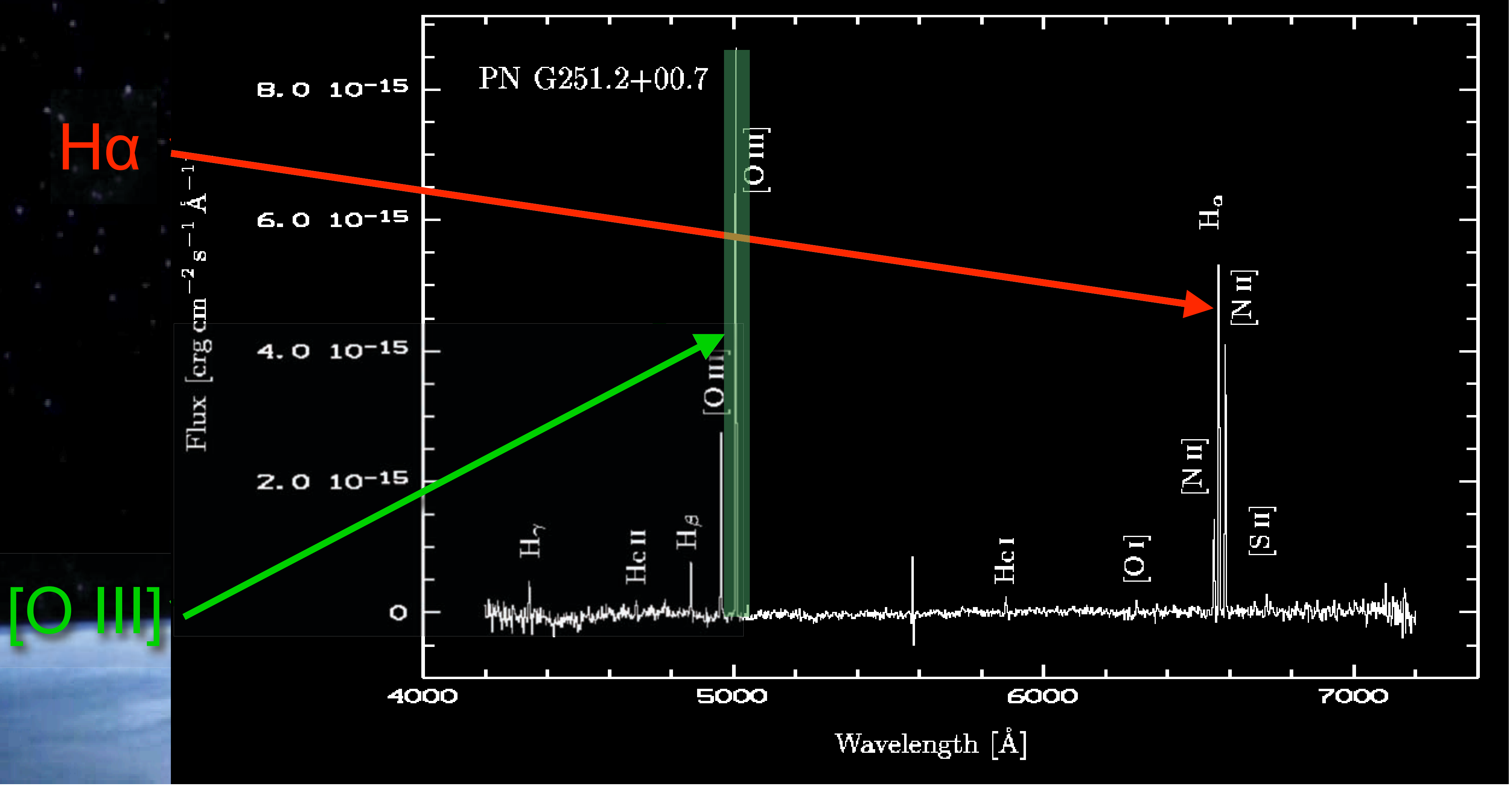
X-rays not useful for mass profiles until gas physics understood?

Extragalactic planetary nebulae

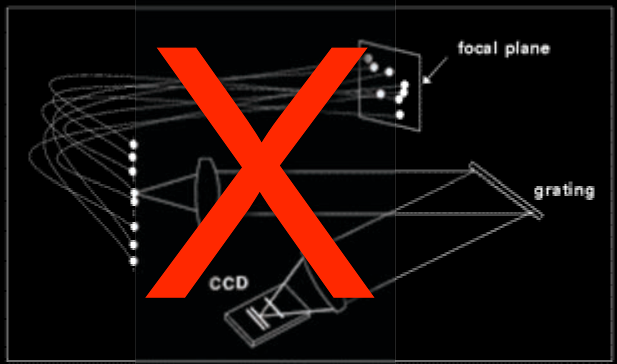
dying stars casting off outer layers of ionized gas

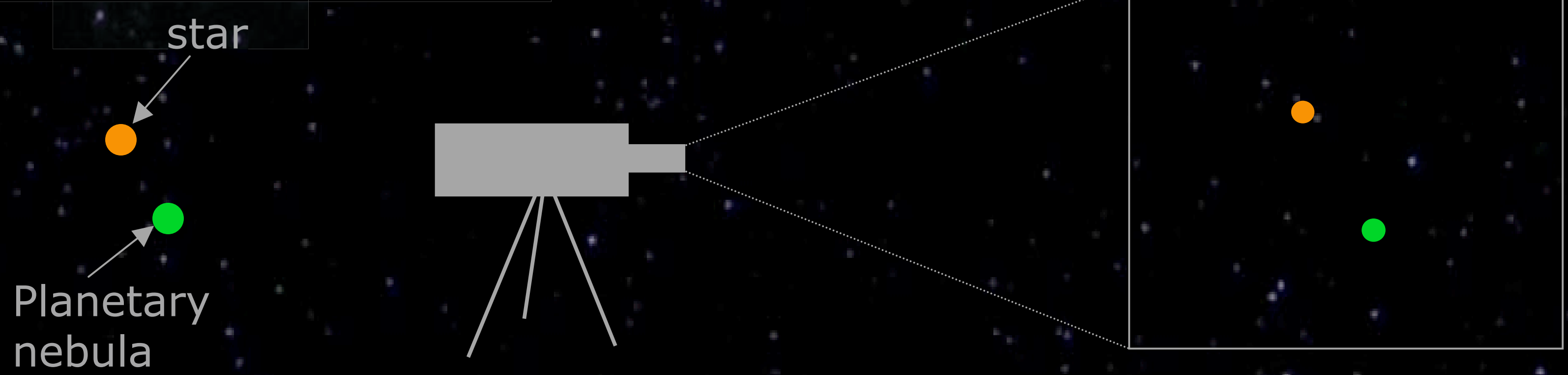
10% of the energy comes out at 500.7 nm “forbidden” O^{++} line

(“*nebulium*”: Huggins & Miller 1864; 3P-1D transition)



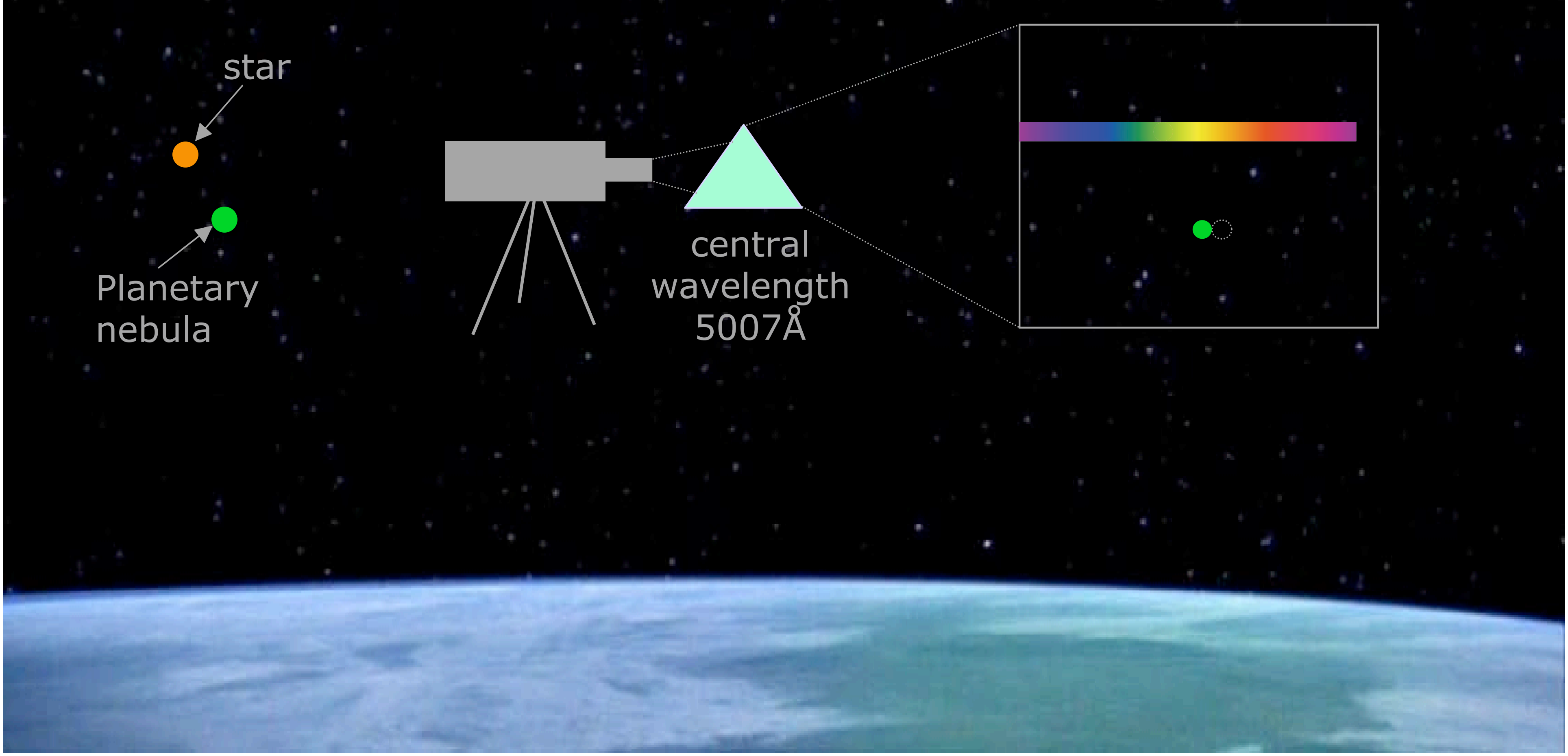
Counter-dispersed imaging



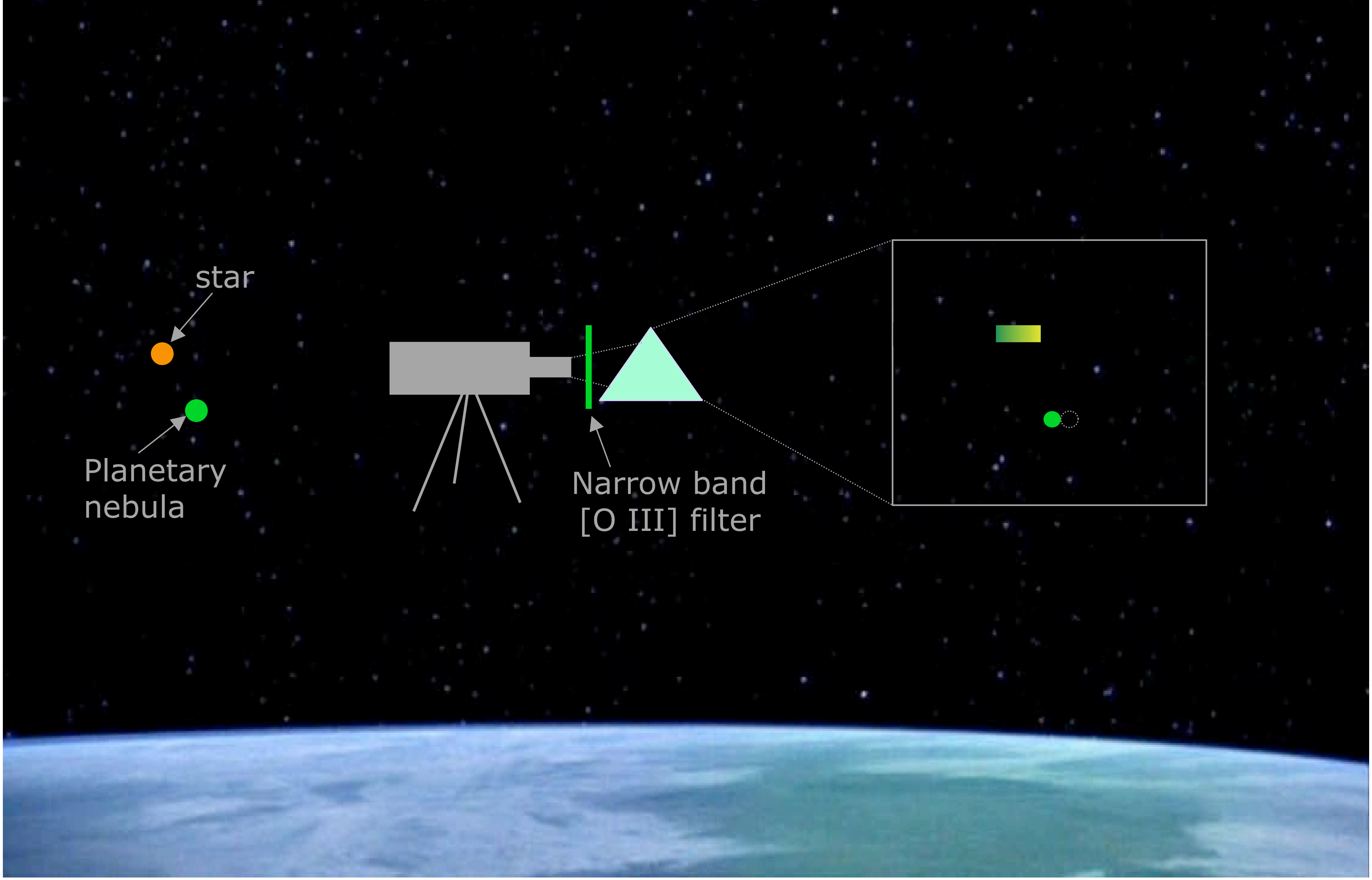


(Douglas & Taylor 1999)

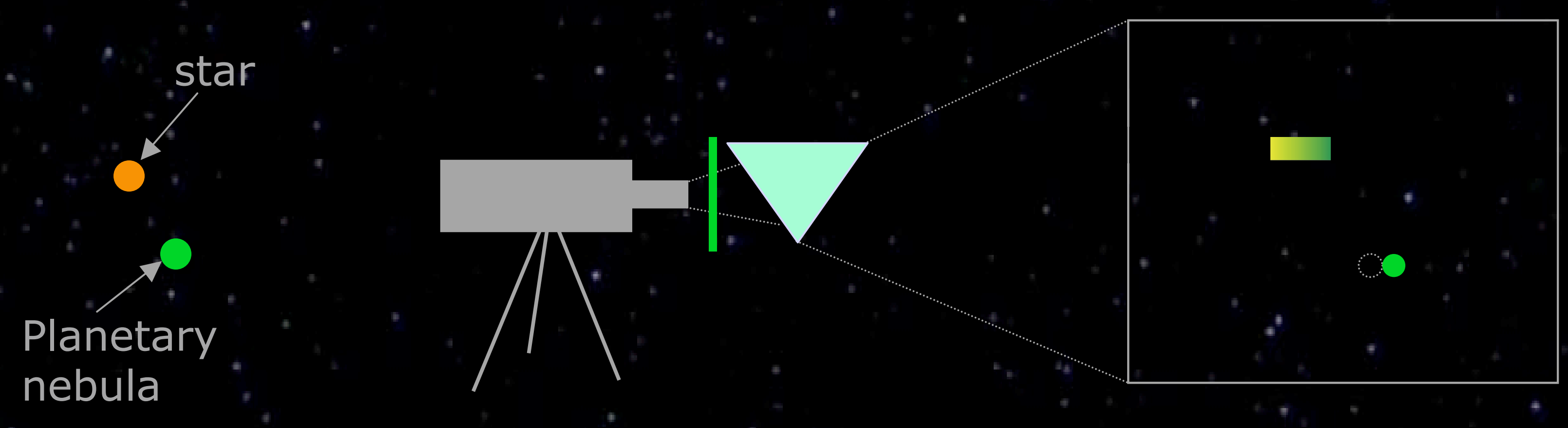
Counter-dispersed imaging



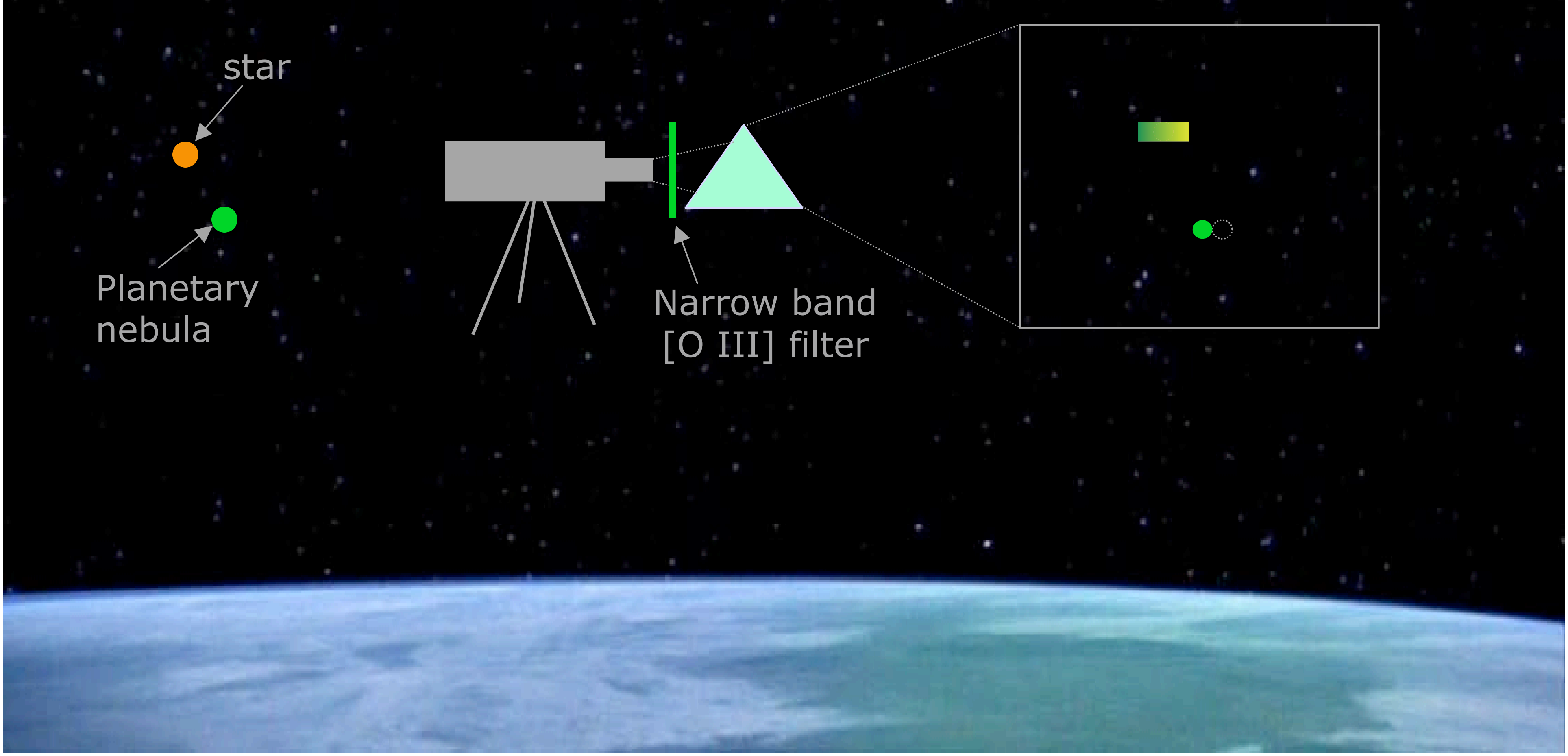
Counter-dispersed imaging



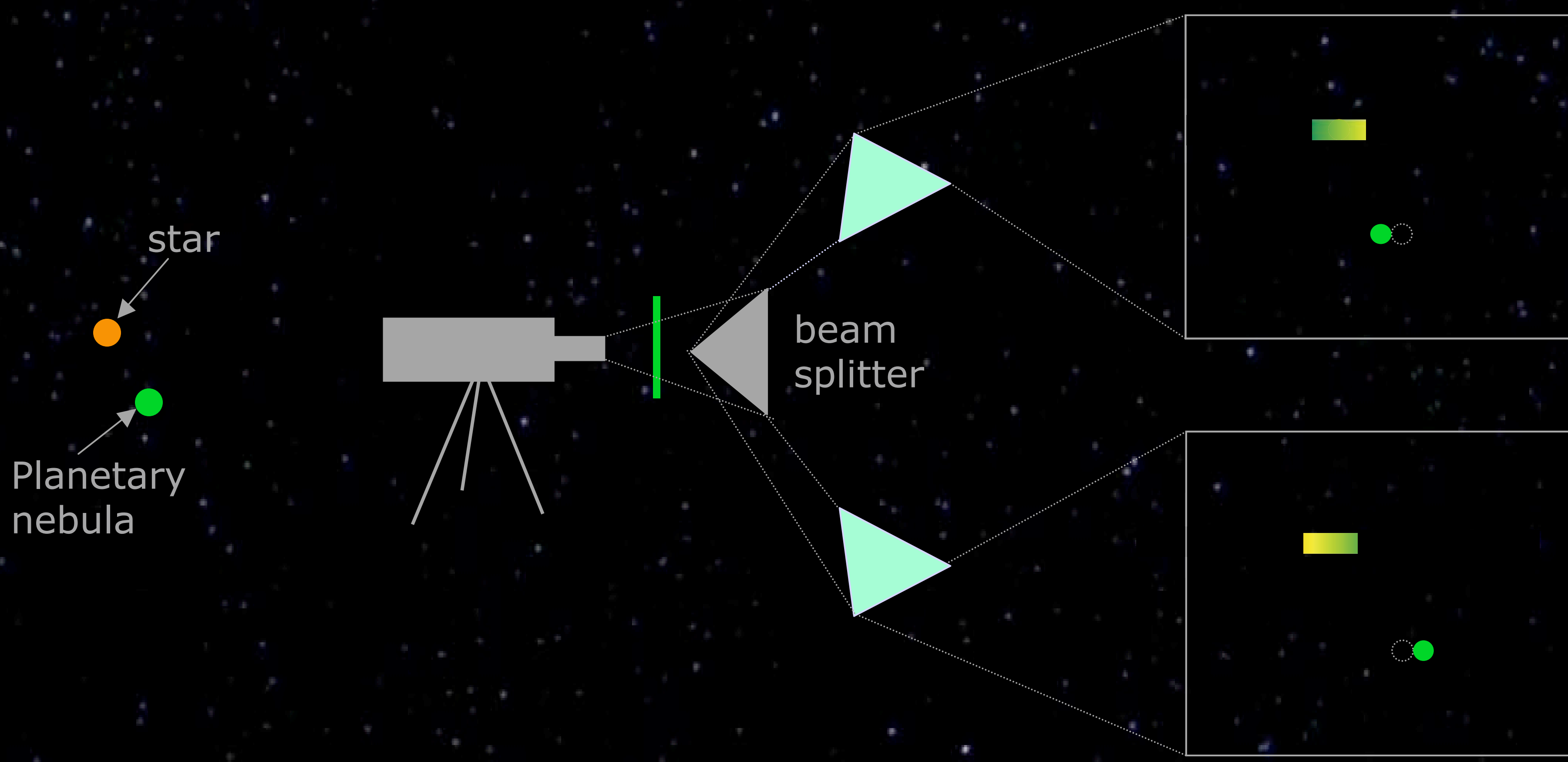
Counter-dispersed imaging



Counter-dispersed imaging



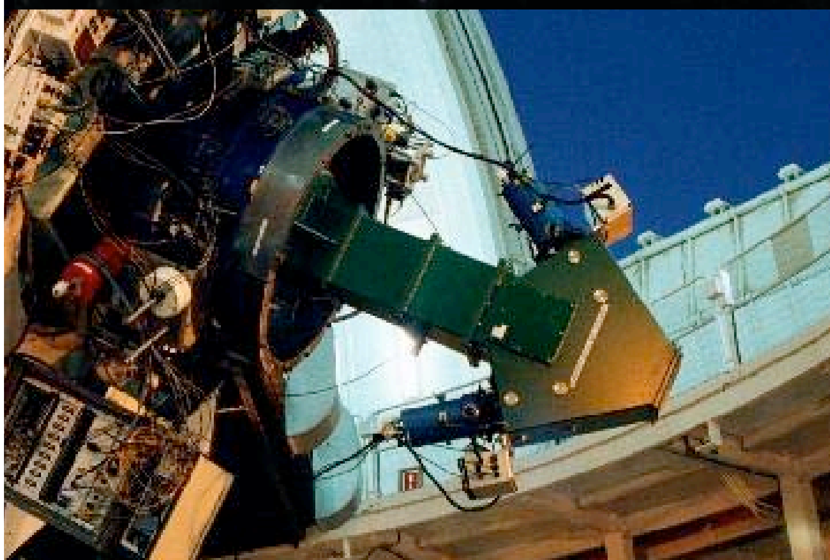
Counter-dispersed imaging

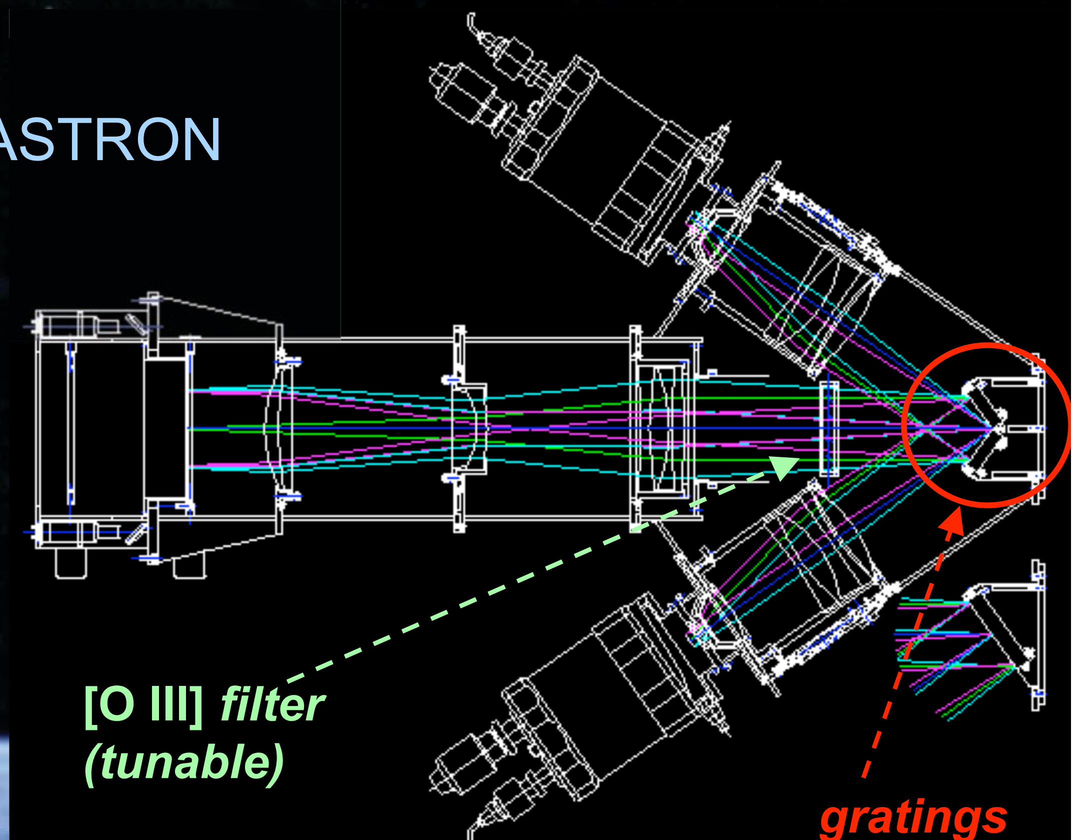


positions & velocities in one go!

Planetary Nebula Spectrograph (PN.S)

- Cassegrain mount at 4.2m WHT (Douglas et al. 2002)
- Instrument efficiency = 72%
  ⇒ total system efficiency = 33%
  (~2x general purpose!)
- Field of view = 11.4’ x 10.3’
  (50 x 50 kpc in Virgo Cluster)
- Built by Prime Optics, RSAA, ASTRON





PNe: slitless spectroscopy

PN.S

5' x 2' (1 kpc x 0.5 kpc) field in M31 (Merrett et al. 2006)

PNe in M31

PN.S

Sb , M_B = -21.2

***D* = 0.8 Mpc**

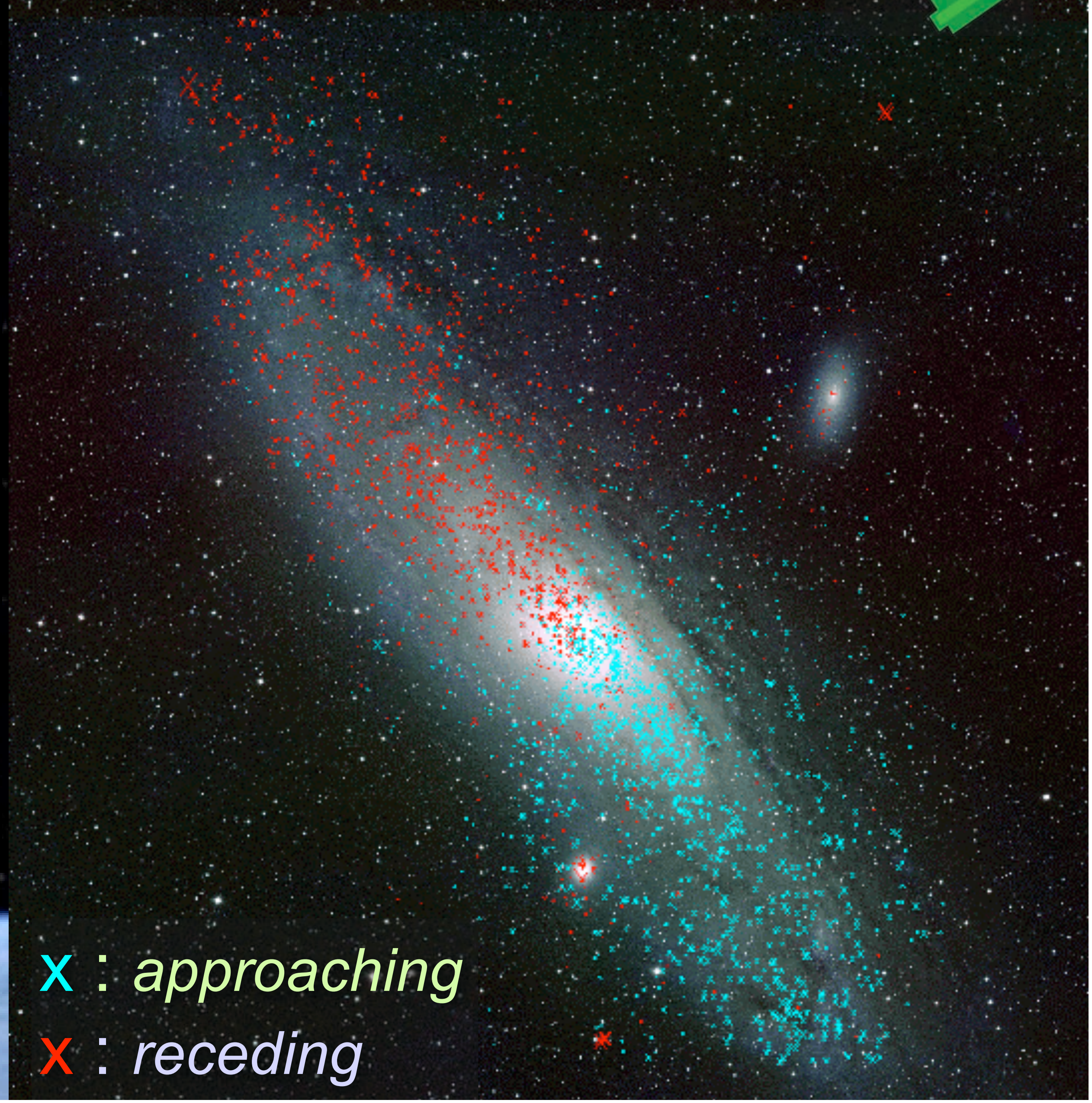
WHT+PN.S, WYFFOS:

Oct 2002, 2003

9 nights :

2615 PN velocities over 7 deg^2

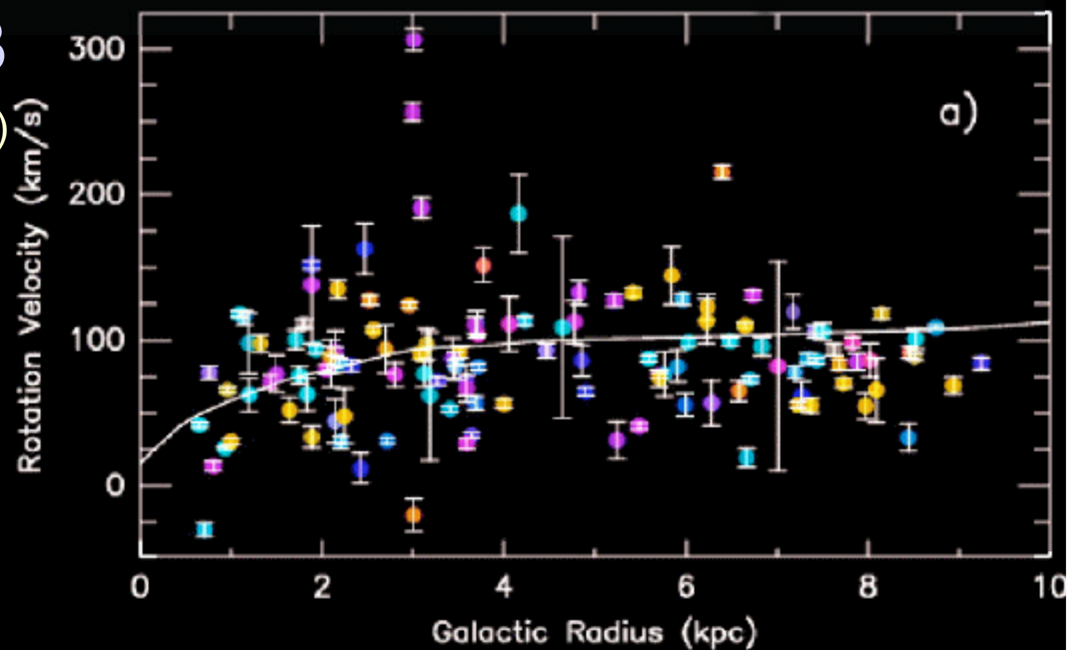
(Halliday et al. 2006; Merrett et al. 2006)



PN-based rotation curves in spirals

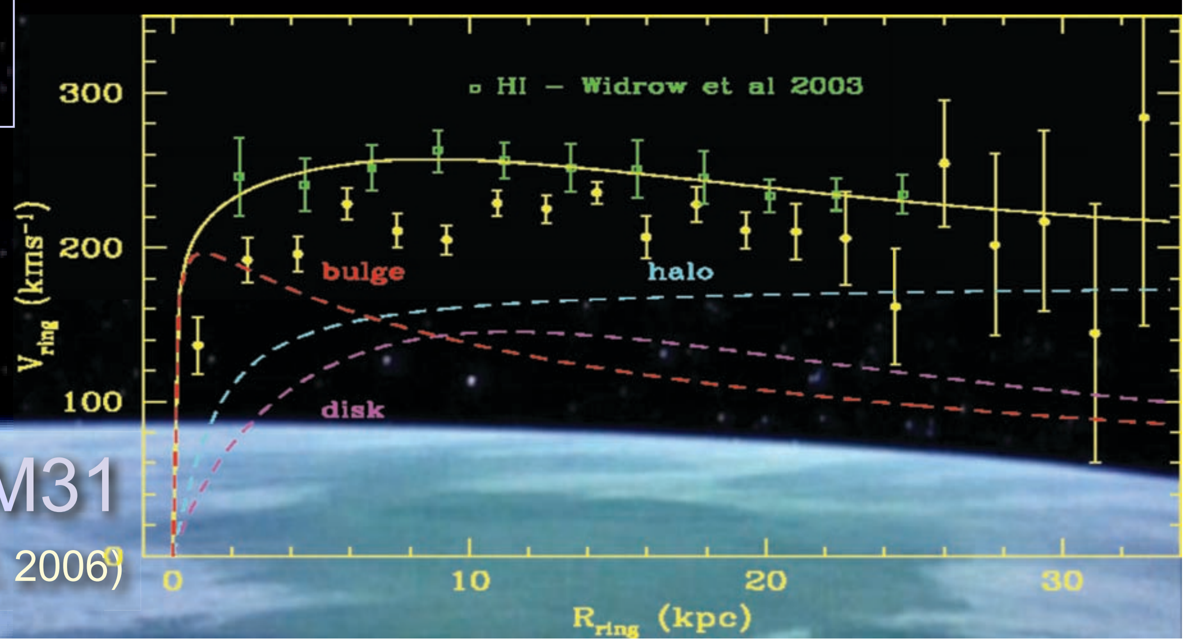
M33

(Ciardullo et al. 2004)



PN circular velocity curves agree with HI, CO (modulo asymmetric drift)

Rules out magnetic field explanation for flat curves
(Battaner & Florido 2005)



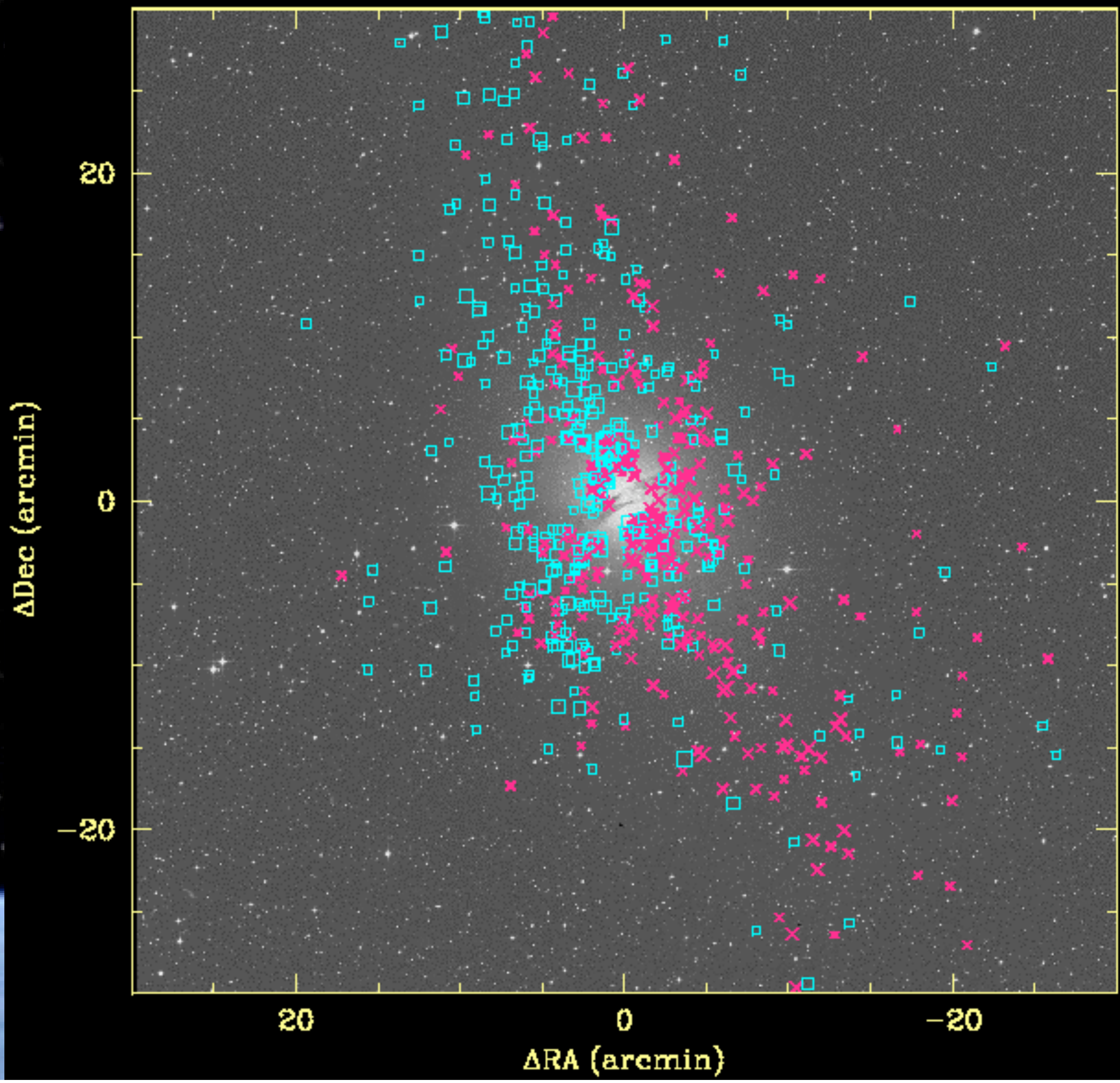
M31

(Merrett et al. 2006)

PNe in NGC 5128

Best-studied early-type galaxy:
E2/S0 merger remnant
D = 4 Mpc
M_B = -20.7

780 PN velocities with AAT, CTIO
(Peng et al. 2004)



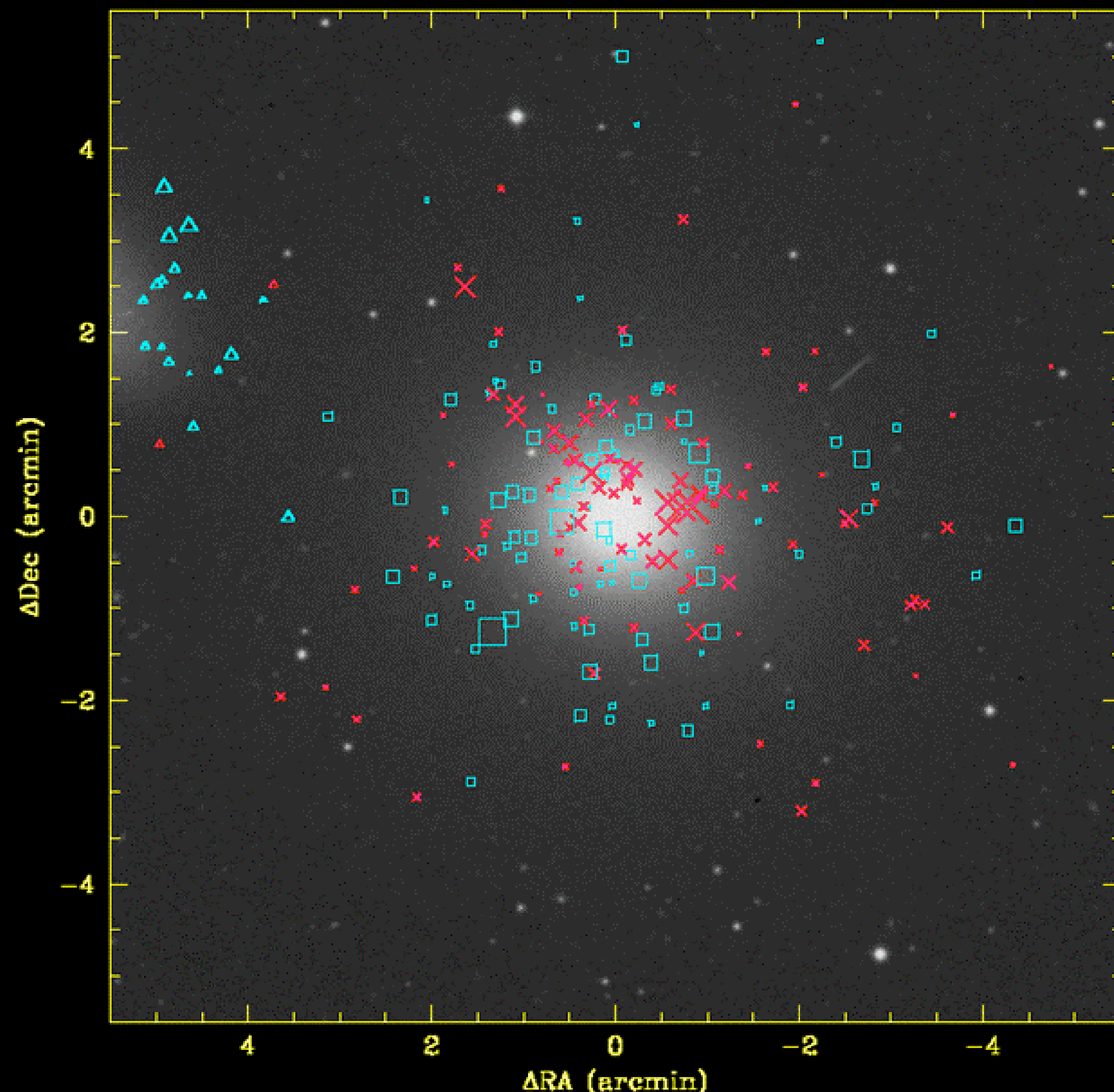
PNe in NGC 3379

E1 , M_B = -19.9 (~L^*)
D = 10 Mpc
Leo I central
"ordinary" elliptical,
fast rotator

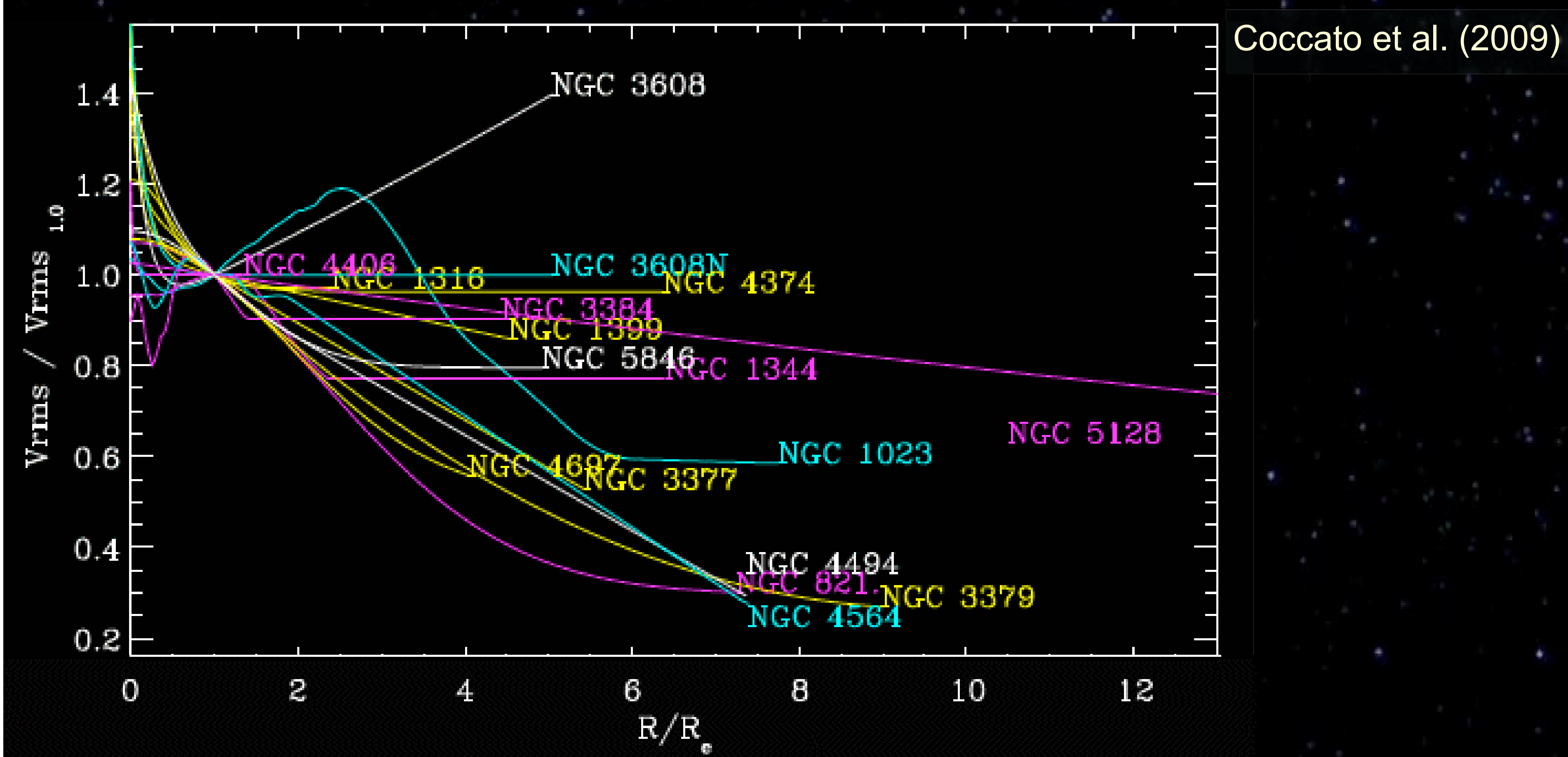
WHT+PN.S:

186 PN velocities
to 8 $R_{\rm eff}$,
Δv = 20 km/s

Douglas et al. (2007)

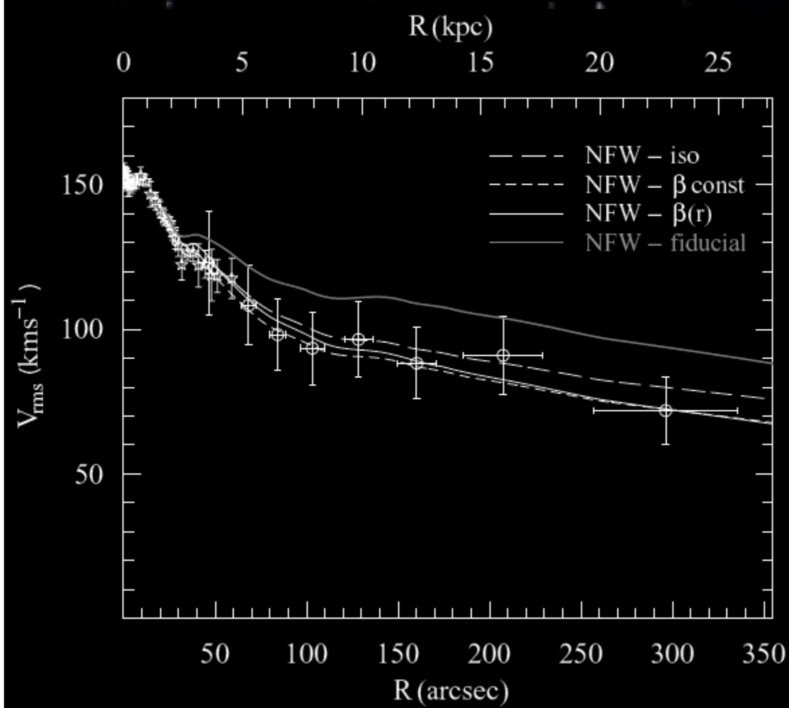


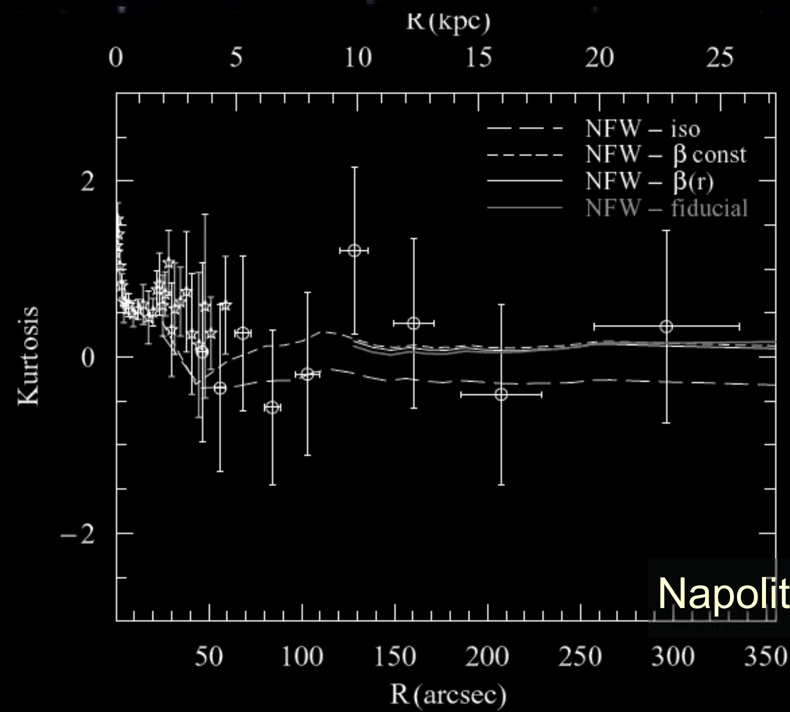
Extended stellar/PN dispersion profiles



Bimodality of flat / declining dispersion profiles in ordinary early-type galaxies?

Stellar + PN data: Jeans models



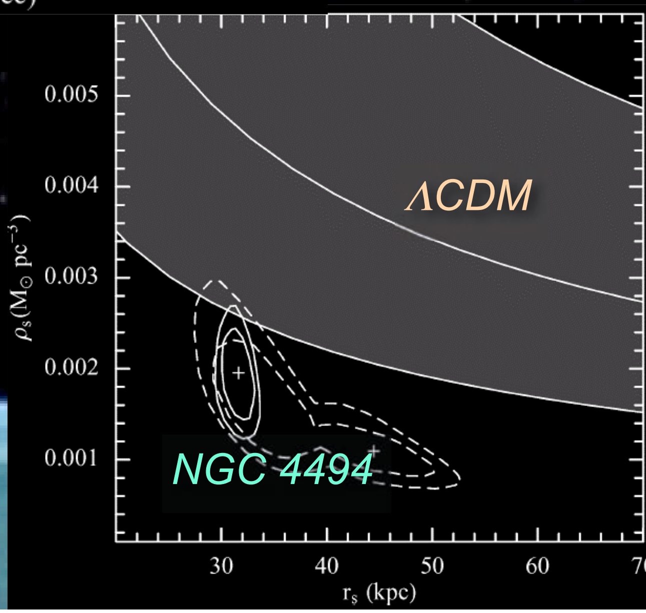


NGC 4494

Napolitano et al. (2009a)

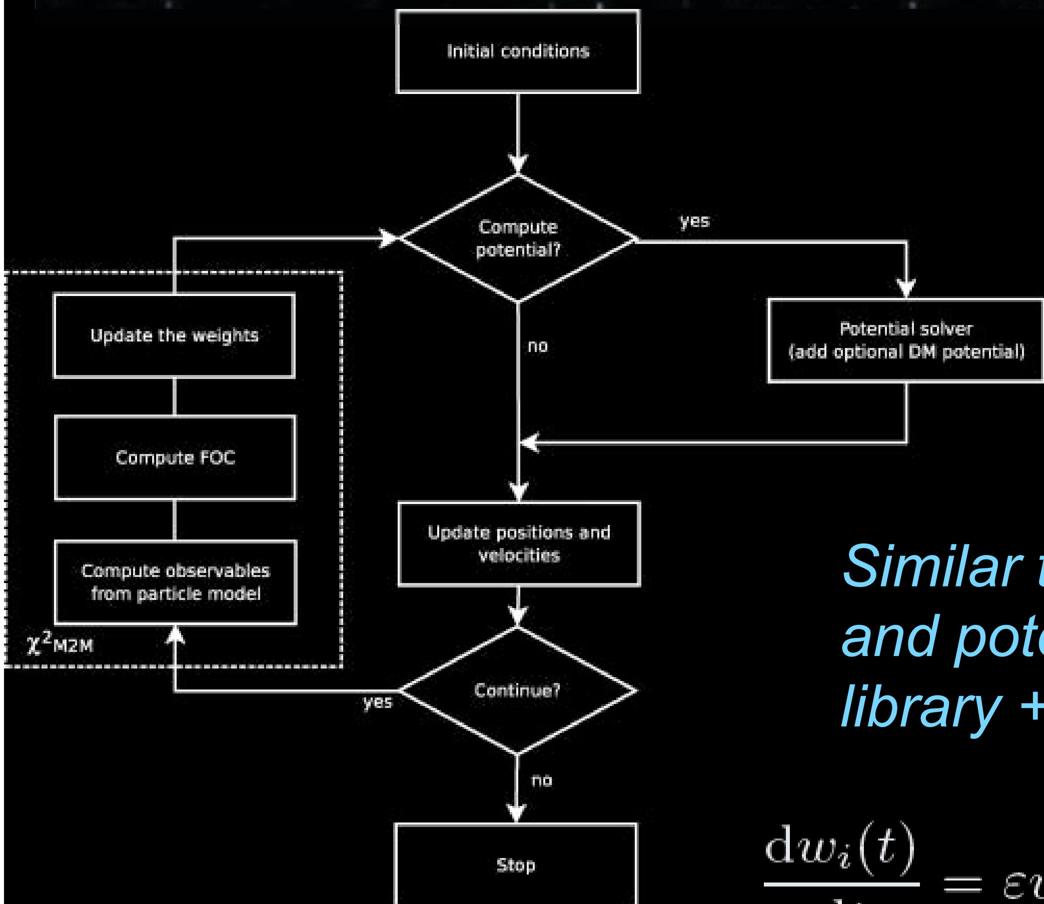
Fourth-order Jeans equations
(β simplifications)

Lower-density halo than ΛCDM
at 1-σ (σ_8=0.9)



Particle-based models (“made-to-measure”)

(Syer & Tremaine 1996; Bissantz et al. 2004; De Lorenzi et al. 2007, 2008, 2009; Jourdeuil & Emsellem 2007; Dehnen 2009)



Similar to orbit models but “live”density and potential evolve (not separate orbit library + fitting stages)

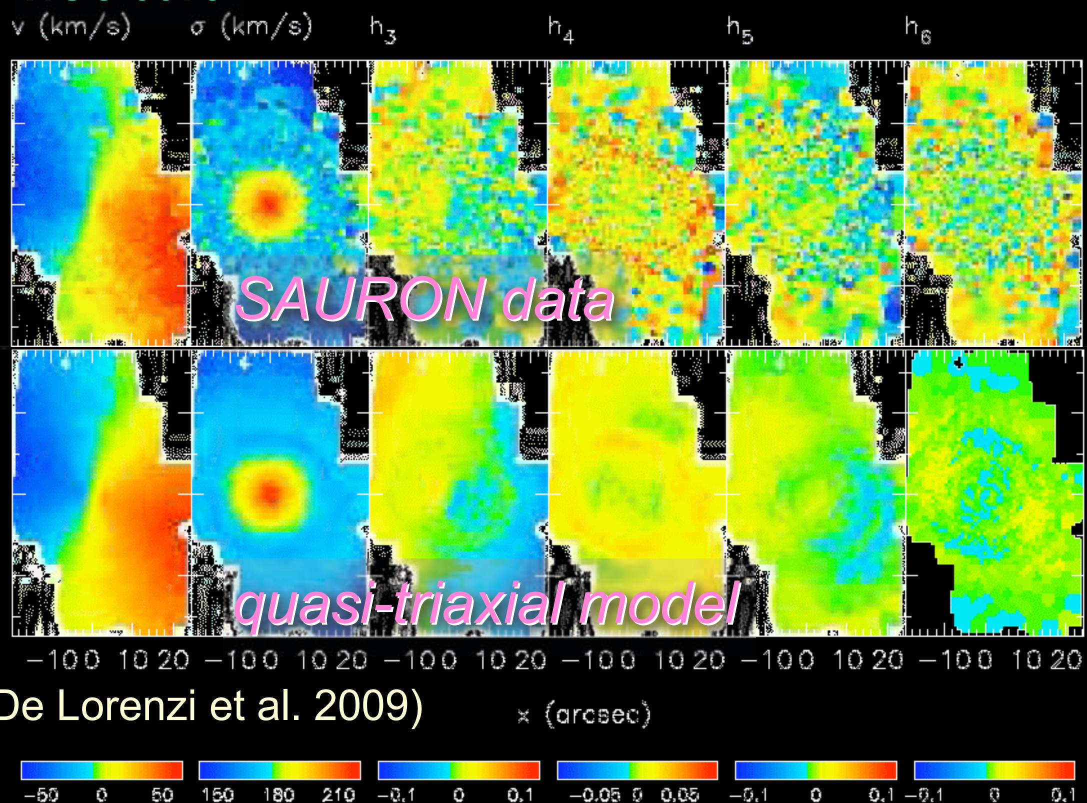
$$\frac{\mathrm{d}w_i(t)}{\mathrm{d}t} = \varepsilon w_i(t) \left(\mu \frac{\partial S}{\partial w_i} - \sum_j \frac{K_j\left[\mathbf{z}_i(t)\right]}{\sigma(Y_j)} \Delta_j(t) \right)$$

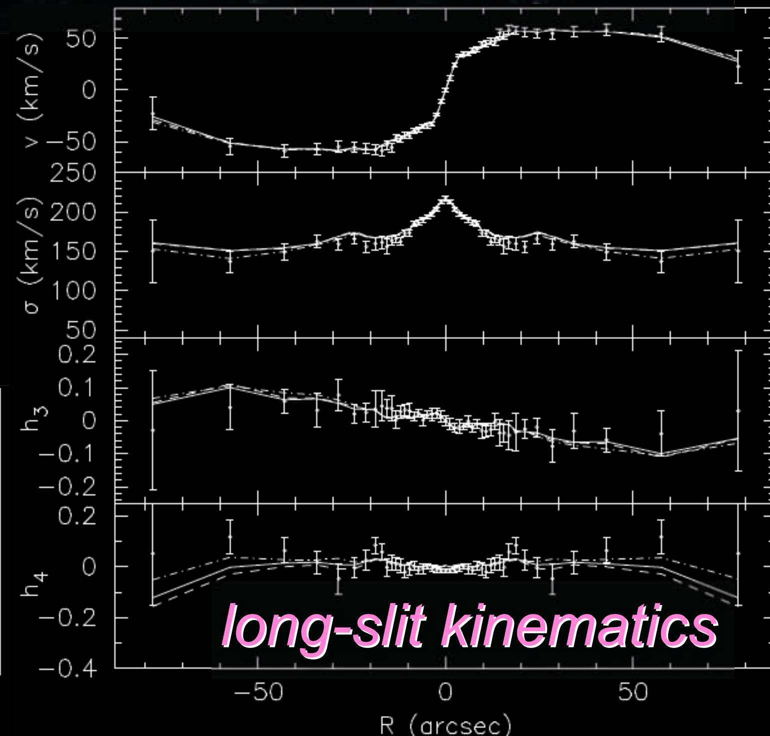
Spherical, axisymmetric, triaxial versions

$$\Delta_j(t) = (y_j - Y_j)/\sigma(Y_j)$$

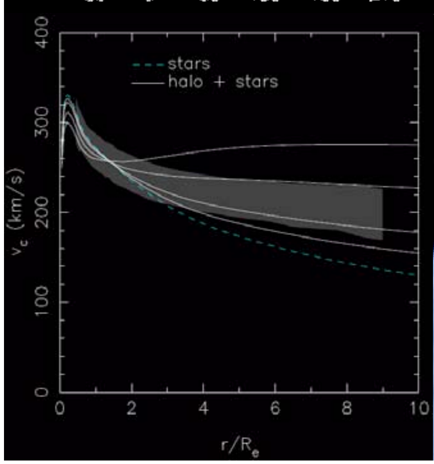
Stellar + PN data: particle models

NGC 3379

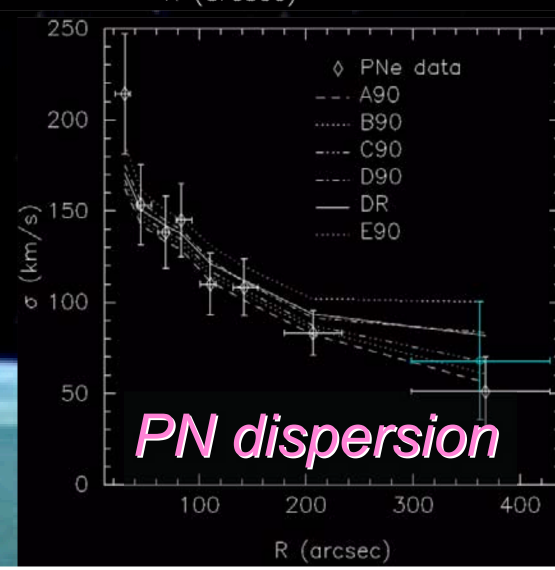




(De Lorenzi et al. 2009)

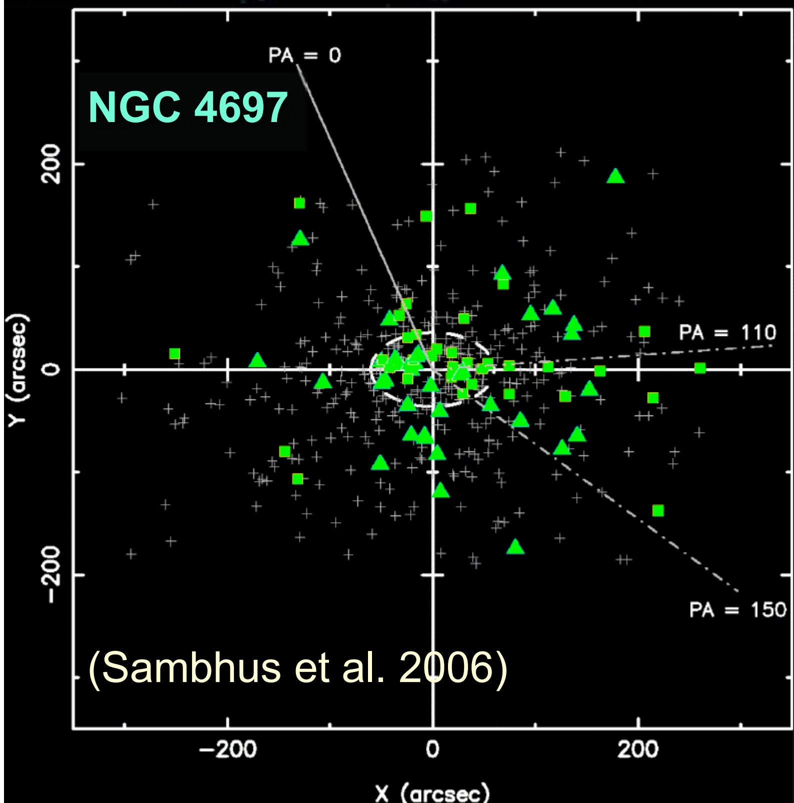


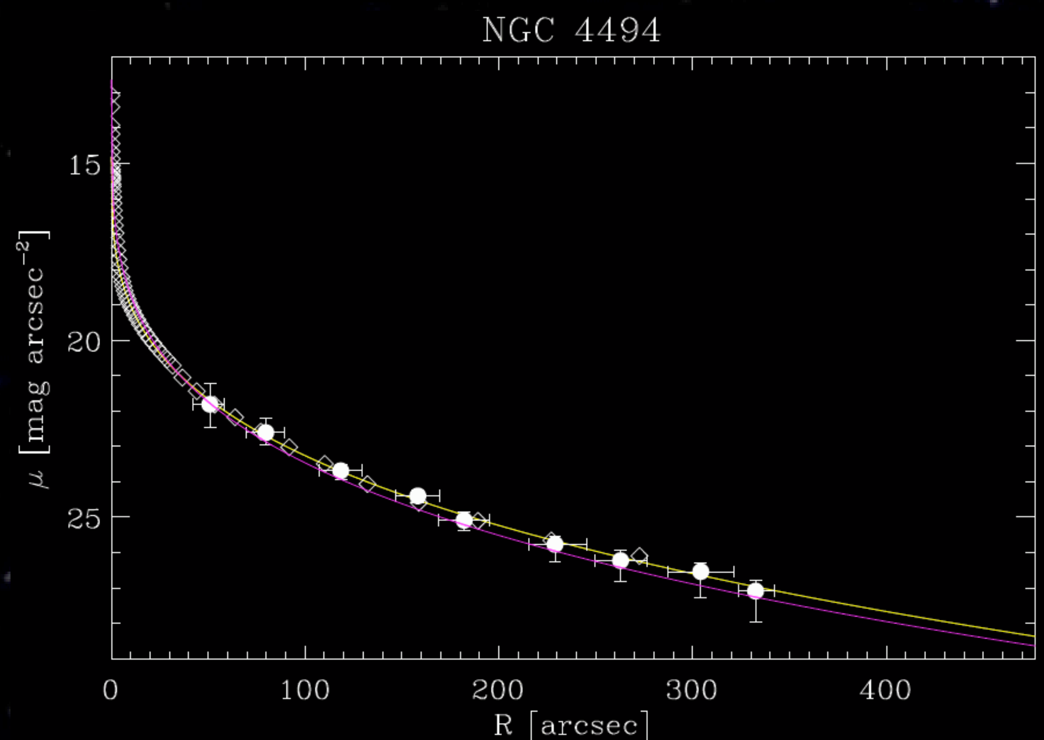
- Rotation field rules out face-on geometry
- DM required but not a lot



Issues in mass estimates from PNe

- *Foreground/background contamination*
- *PN-stellar population link?*





Left/right asymmetry of bright PNe: unmixed young population?

But no systematic differences evident between stars and PNe in surface densities, kinematics in large galaxy sample…

Probes of halo kinematics

Planetary nebulae:

- feasible to 25 Mpc
- more reliable velocities
- well-known spatial distribution
- not affected by dust
- contiguous constraints with central stellar kinematics
- less contamination problem
- more abundant in fainter galaxies
- detection & spectra in one go

Globular clusters:

- feasible to 40 Mpc
- larger radius
- disk less likely
- not affected by dust

(Baes & Dejonghe 2001)

Gemini, 16 Feb 2006

Follows: Romanowsky et al. 2003, Science, 301, 1696
Dekel et al. 2005, Nature, 437, 707

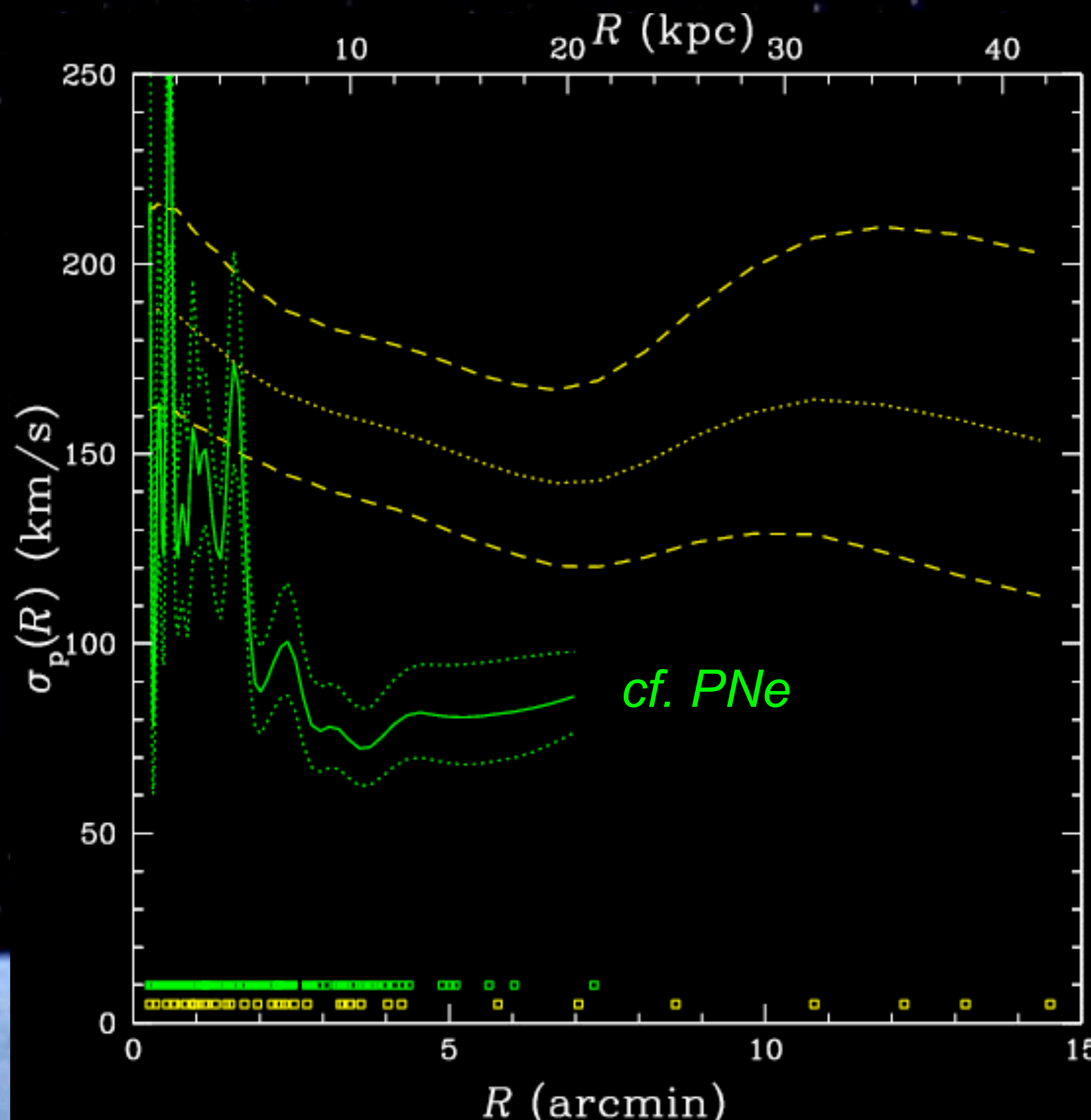
NGC 3379 : GCS dispersion profile

Weakly declining dispersion:

$\sigma_p(R) \propto R^{\gamma}$,
$\gamma = -0.13 \pm 0.12$

Due largely to different $N(R)$, $\beta(r)$

(Puzia et al. 2004; Pierce et al. 2006; Bergond et al. 2006)

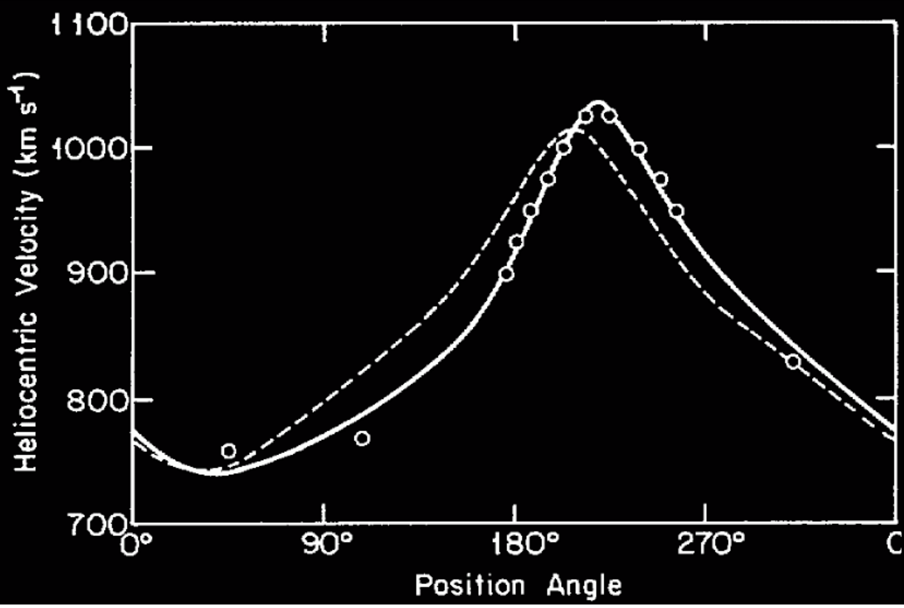


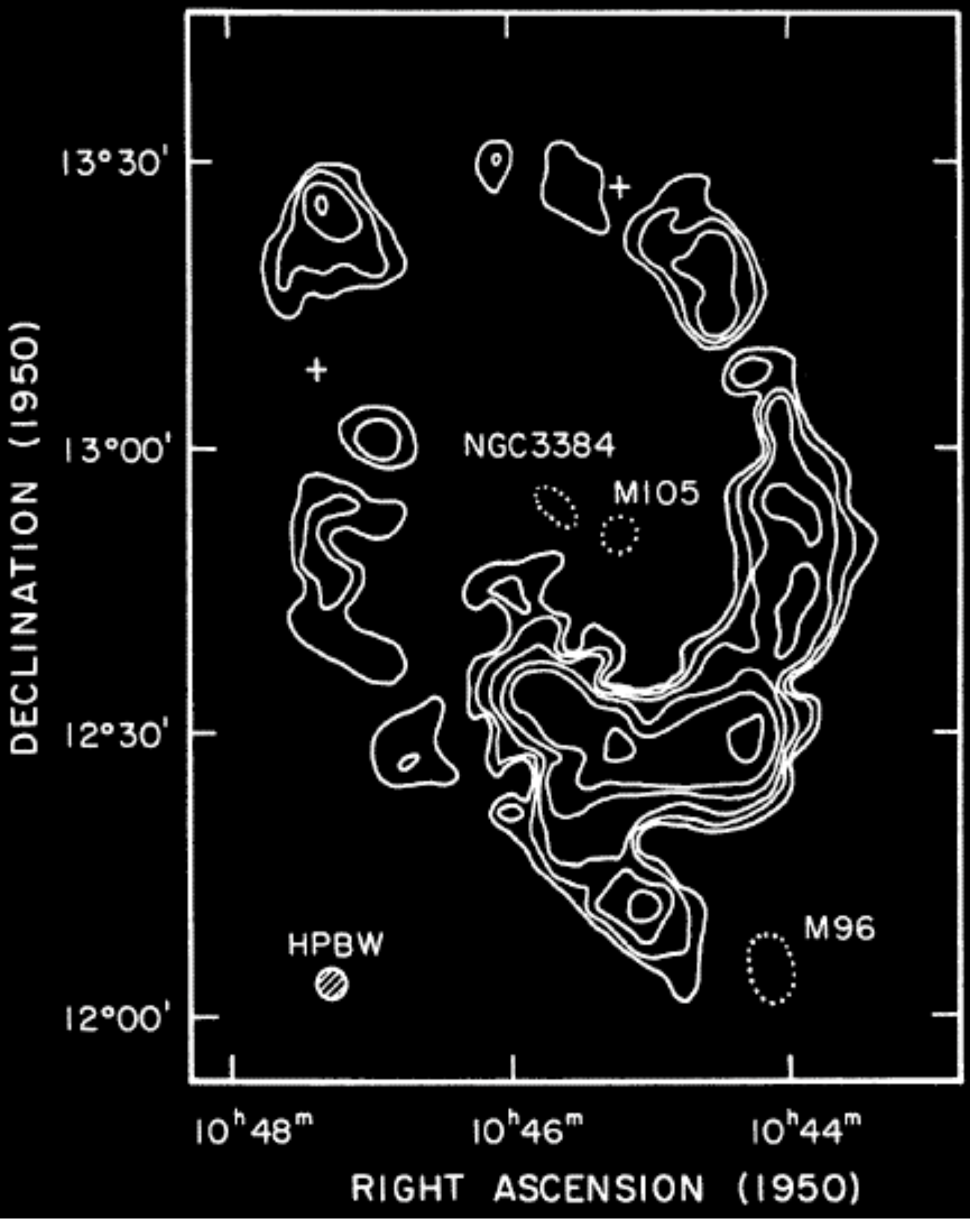
NGC 3379: HI gas ring

Mass measurement N3379 + N3384:

M/L_B (100 kpc) = 27 ± 5 (Schneider 1985)

Not consistent with group-mass halo

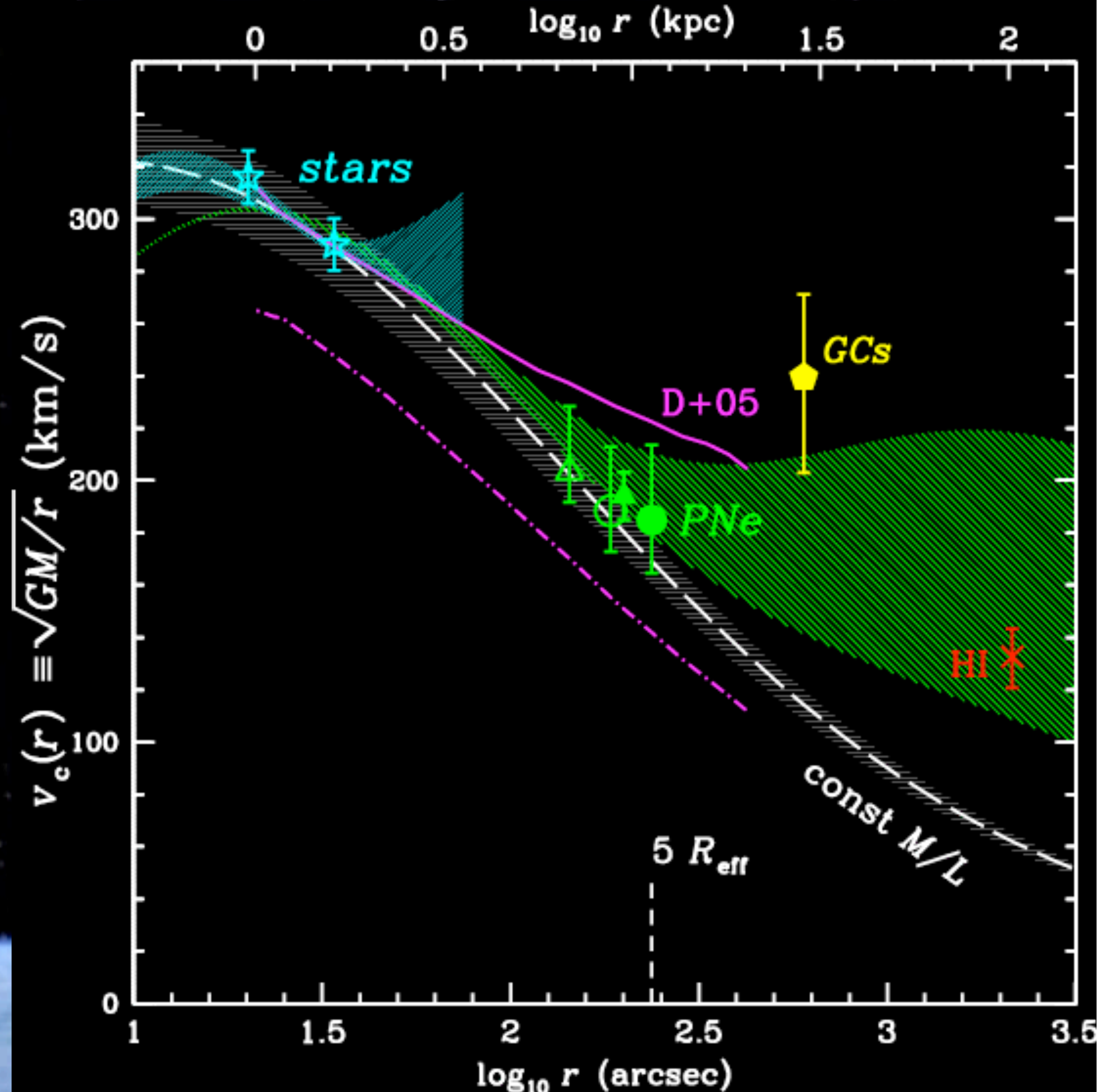




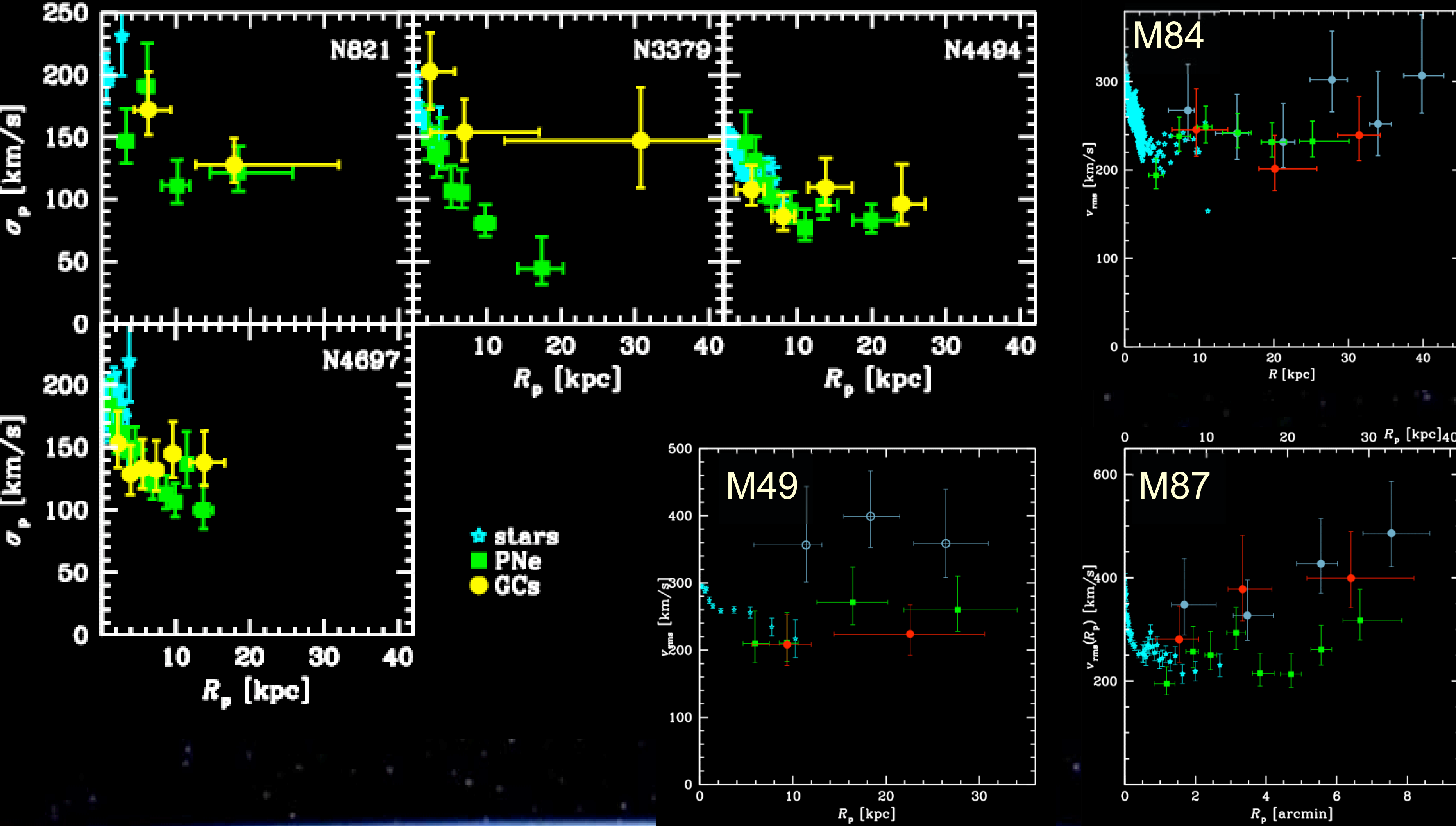
Multiple mass probes in NGC 3379

Difficulty harmonizing both GC, HI constraints

Nearby companion (NGC 3384) → halo not in equilibrium?

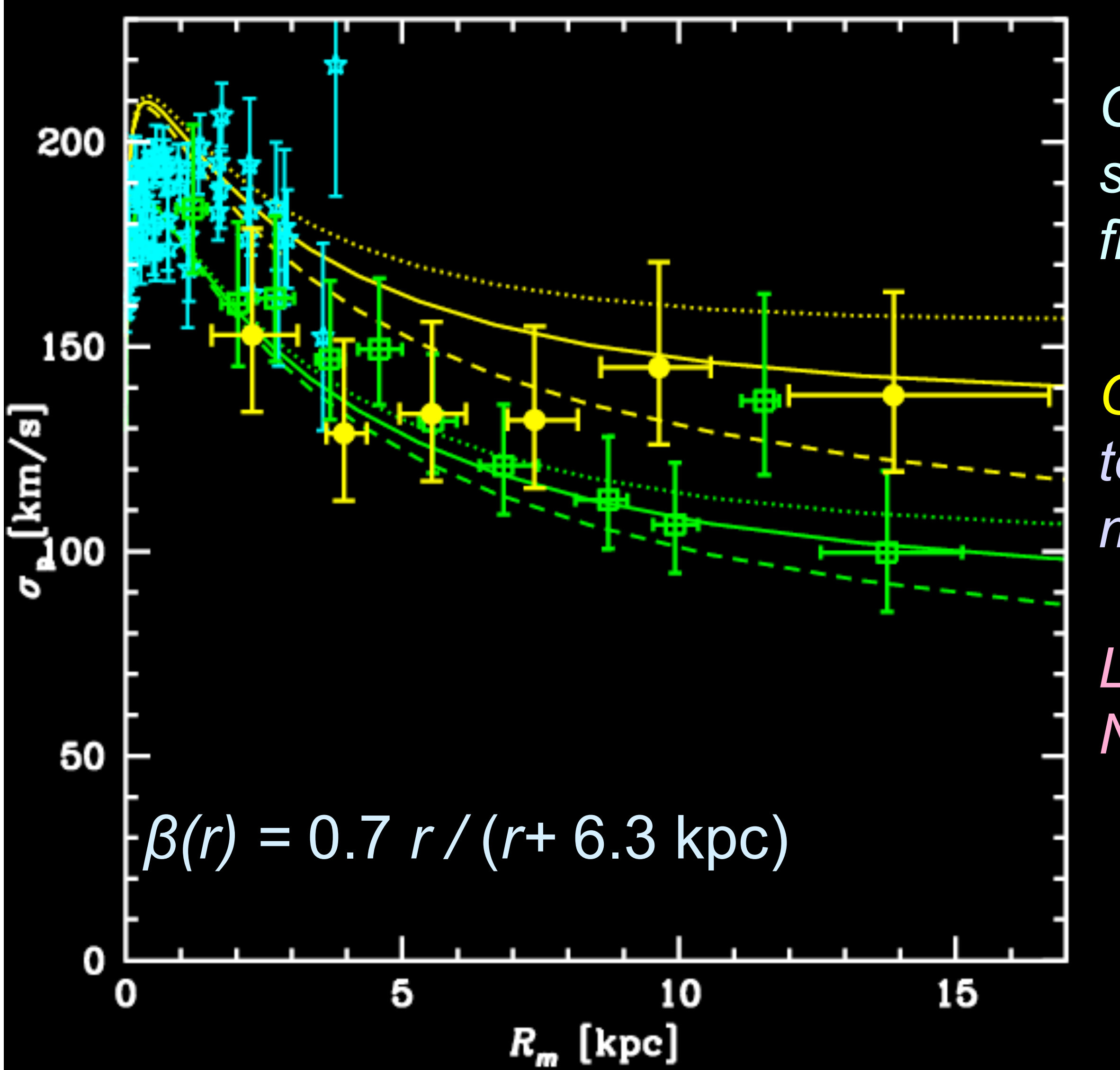


Comparing PN + GC dispersions



5 cases with fairly similar dispersions, 2 discrepant

Independent mass results in NGC 4697

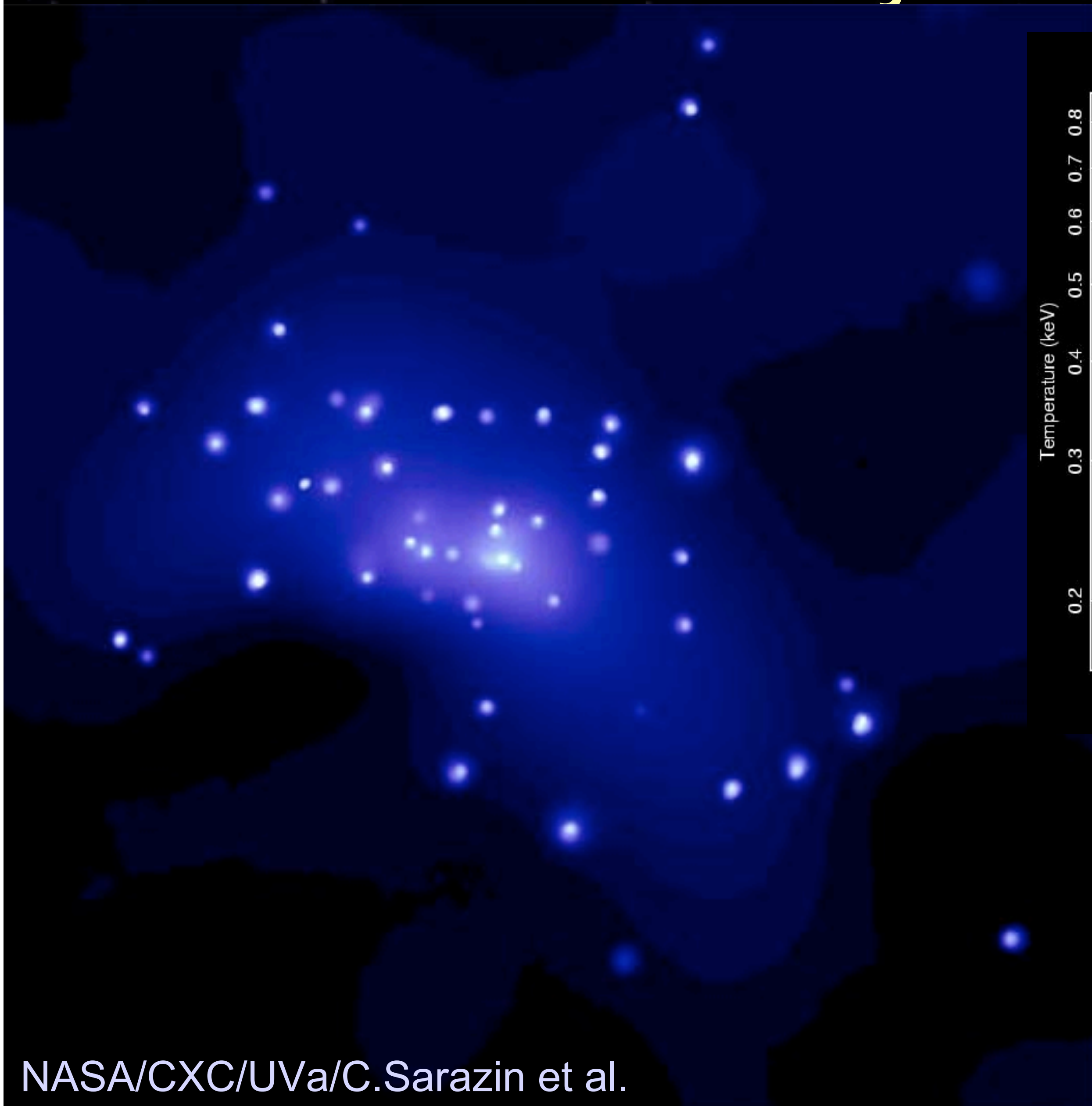


Crude spherical model gives same results as sophisticated flattened model!

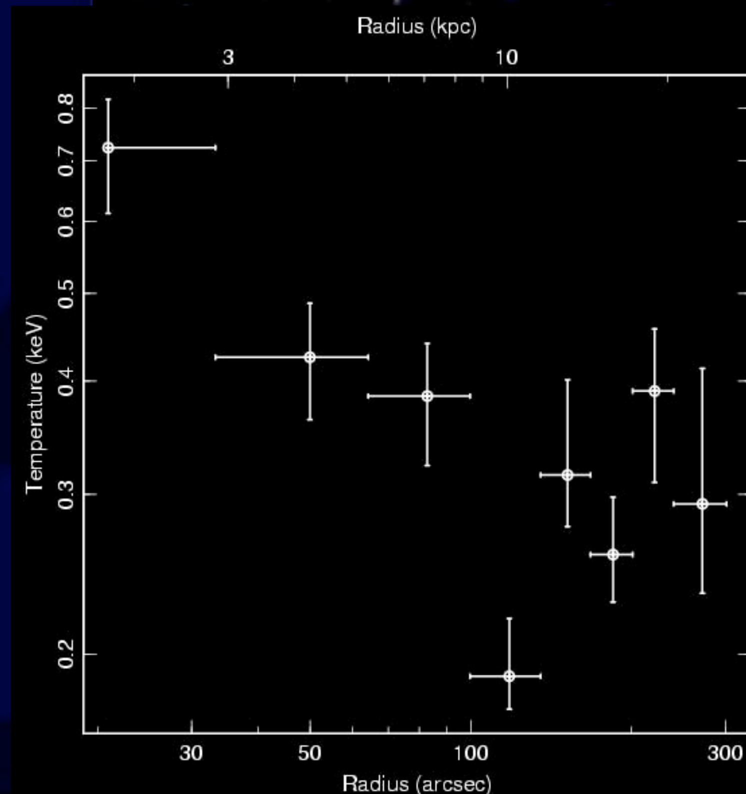
GCs more sensitive than PNe to halo mass because more radially extended

Lower-mass DM halo from NMAGIC solutions preferred

Mass from X-rays: NGC 4697

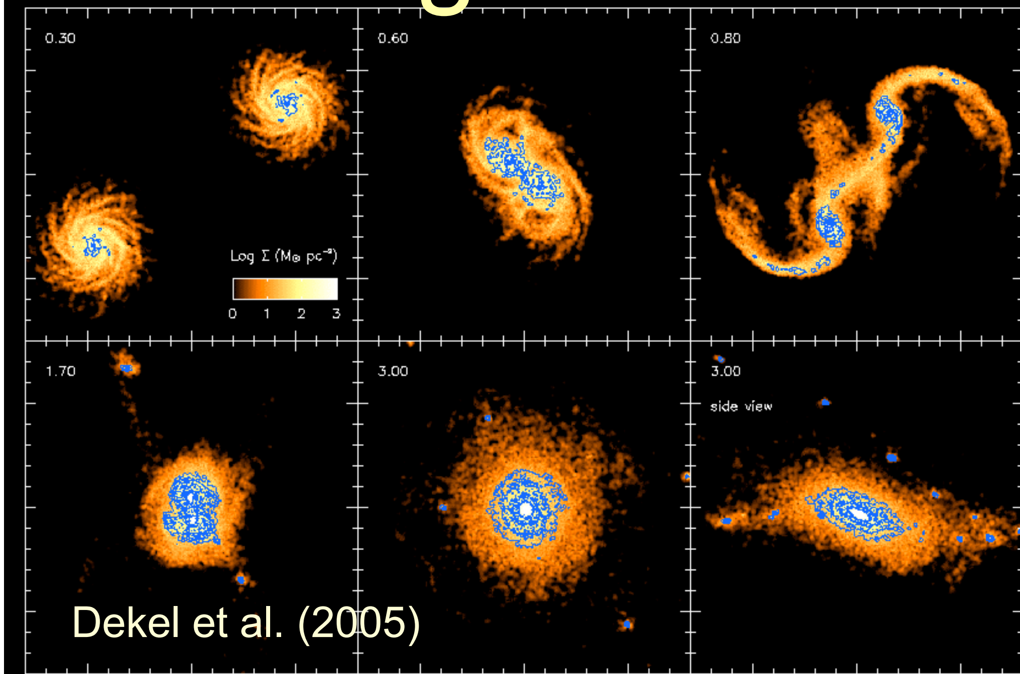


NASA/CXC/UVa/C.Sarazin et al.



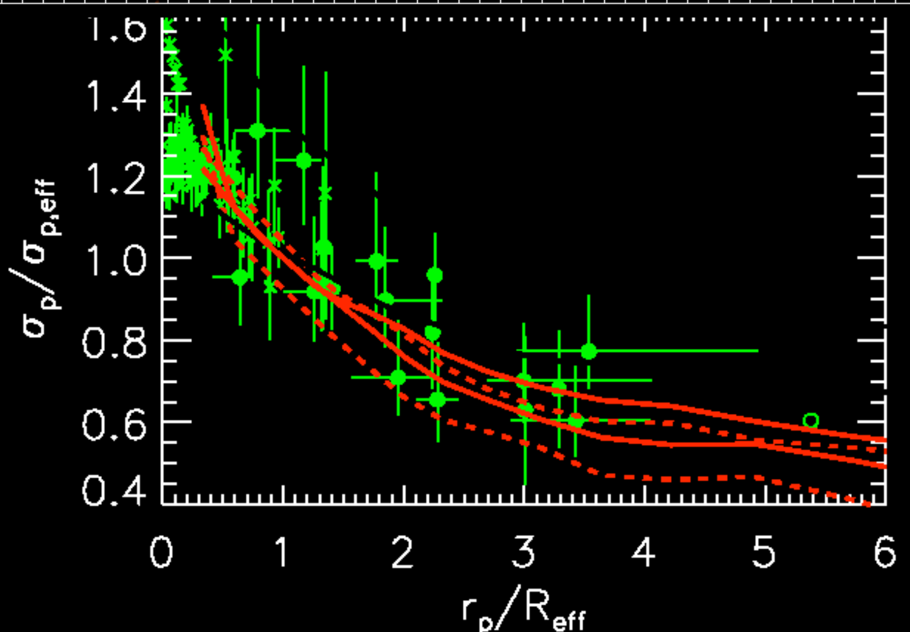
R. Johnson et al., in prep.

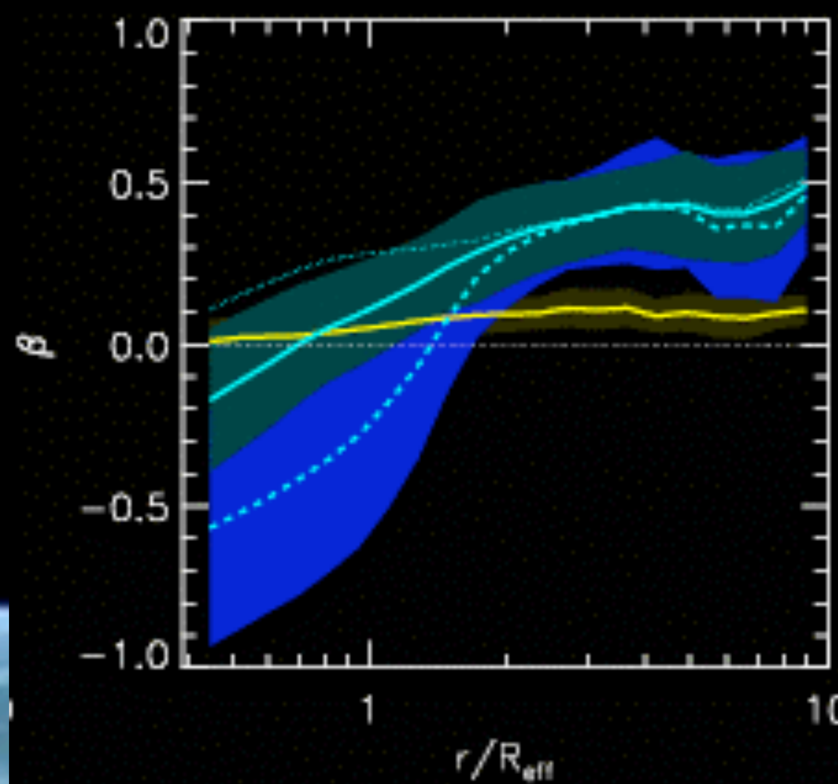
Matching observations to simulations



Simulations of "wet" galaxy mergers naturally produce declining dispersions

- *primarily from radial anisotropy in halo*



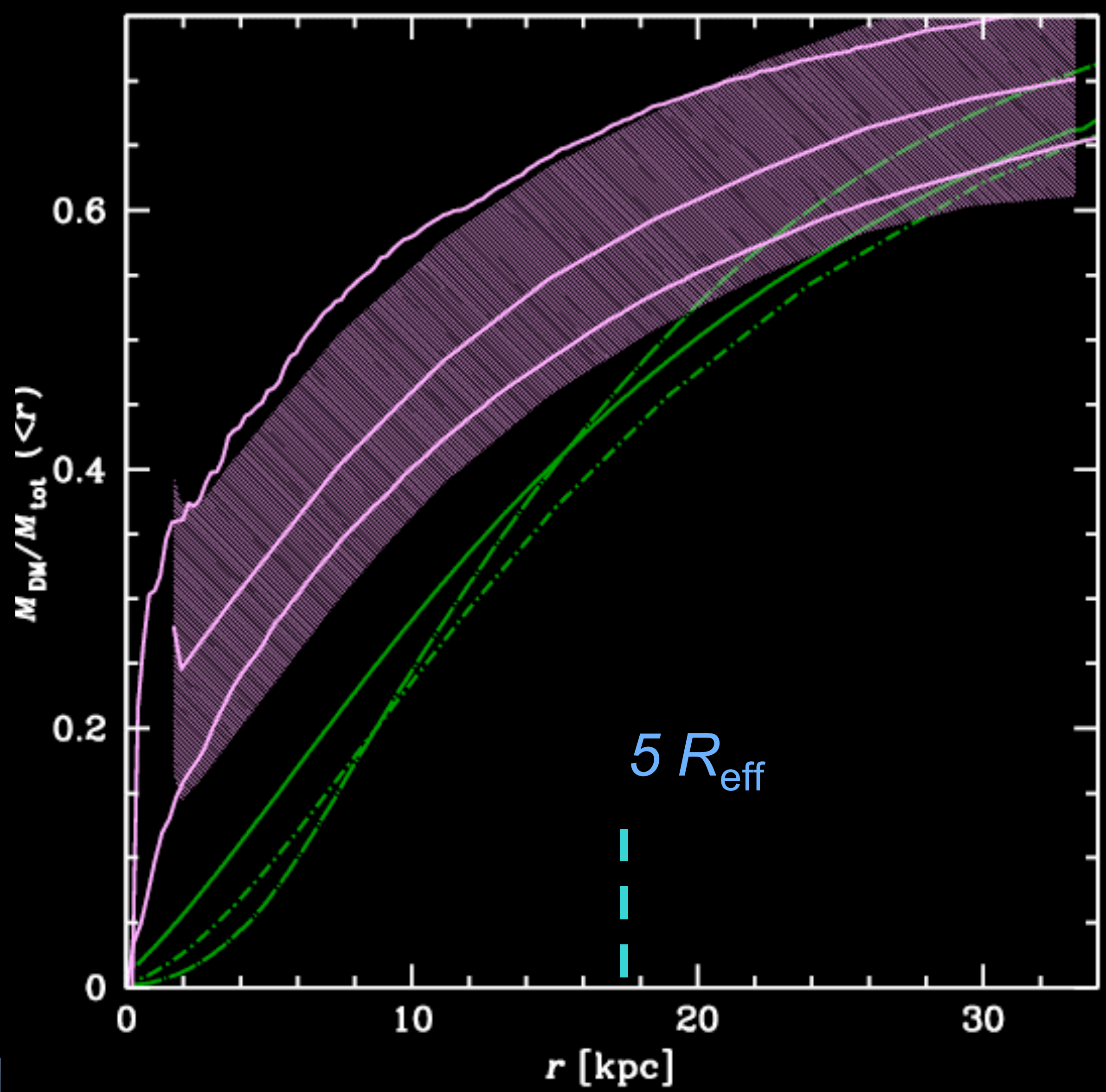


Mass profile decompositions

Simulations including baryon physics
(Dekel et al. 2005;
Naab et al. 2007;
Oñorbe et al. 2007)

Systematic central dark matter difference between simulations and observations (modeled including radial anisotropy)

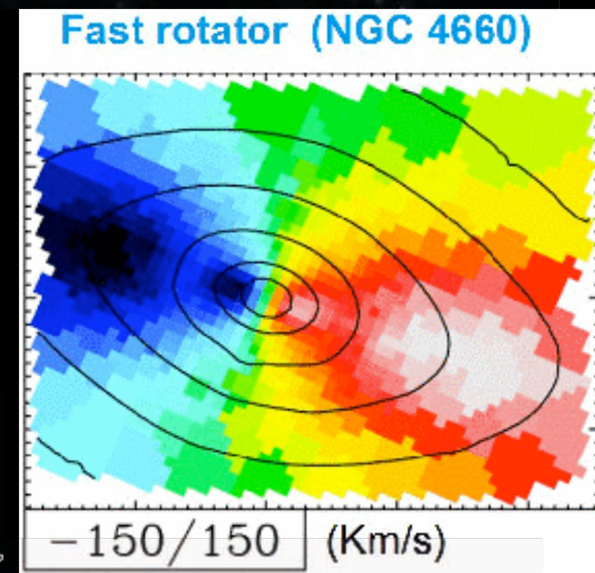
partial stellar *M/L* degeneracy as in spirals



Bimodality of early-type galaxies

Fast rotators = E/S0s ?

- optically faint
- low velocity dispersion
- disky isophotes
- rapid rotators
- cuspy cores
- low X-ray luminosity
- weak radio sources

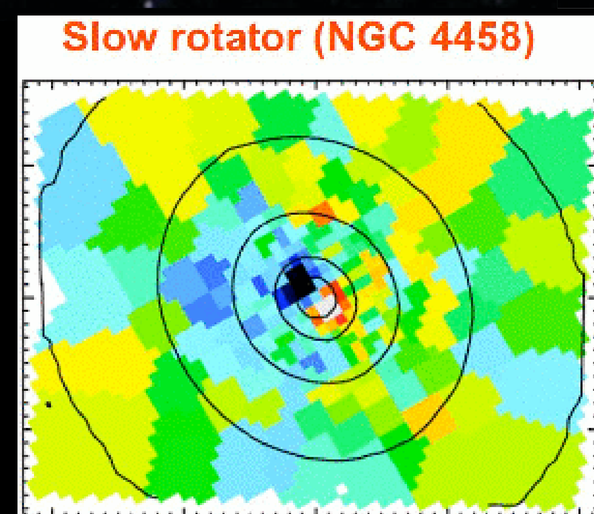


(Kormendy & Bender 1996; Faber et al. 1997)

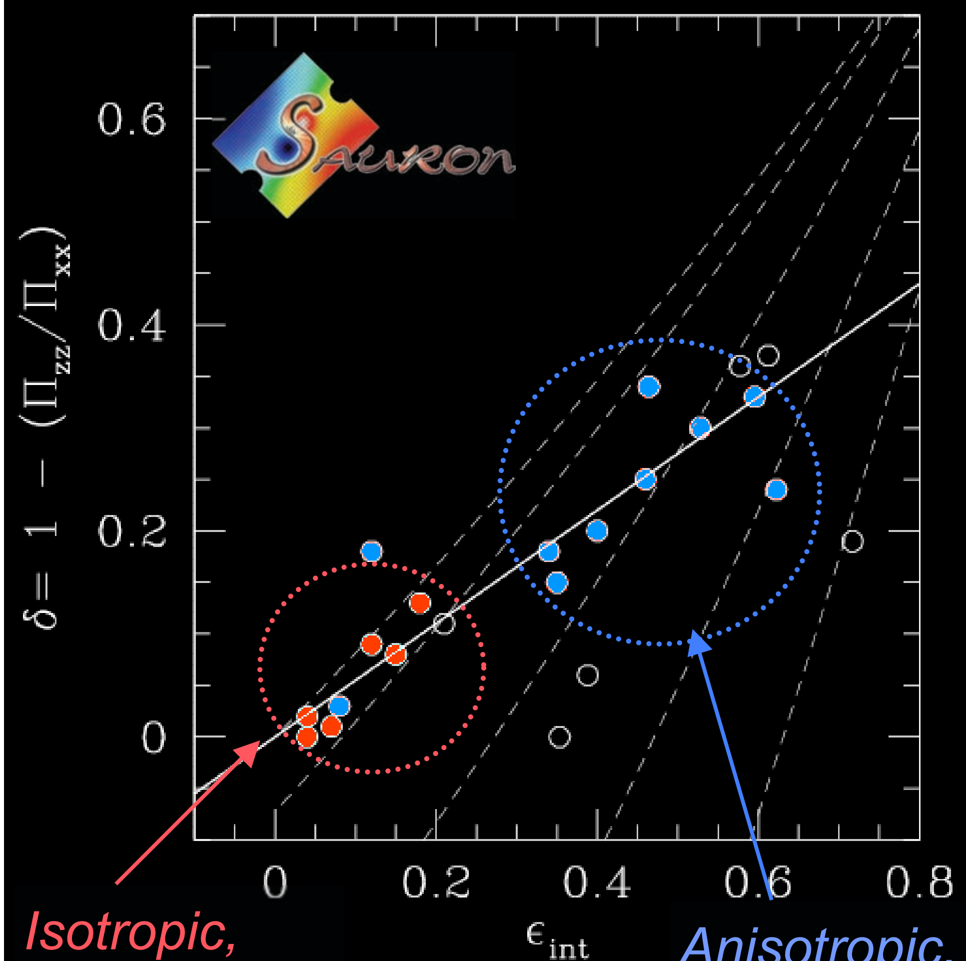
(Emsellem et al. 2007)

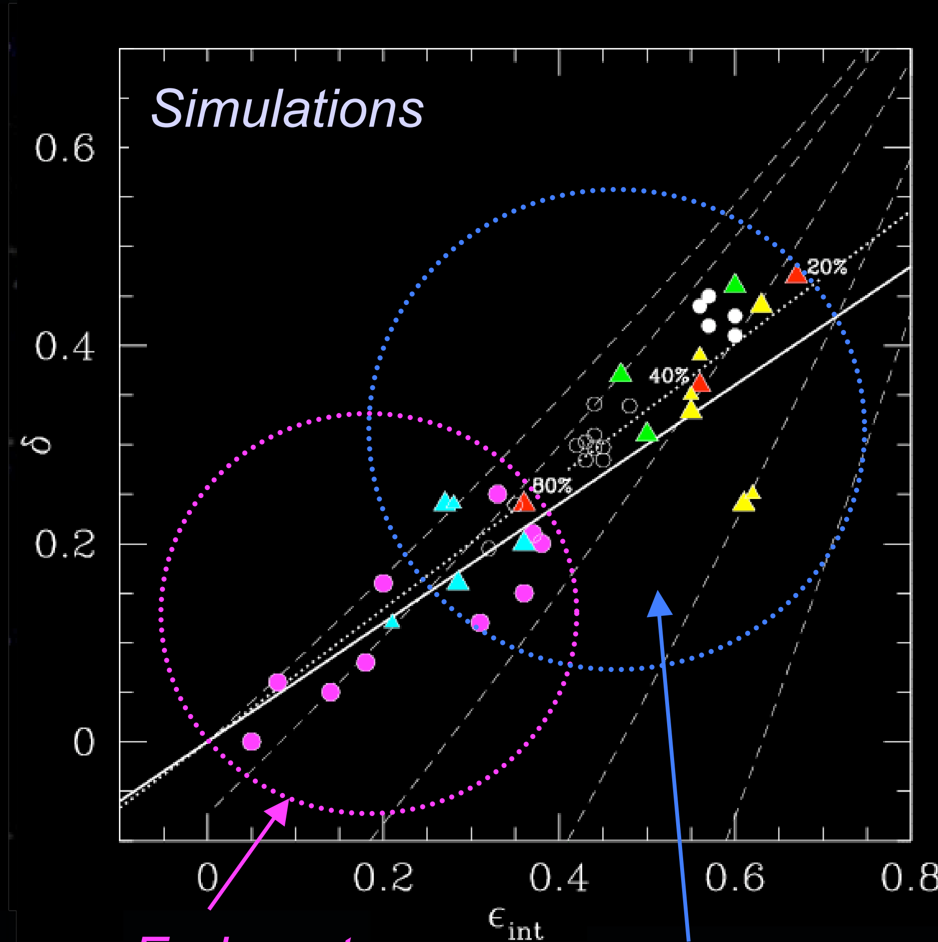
Slow rotators = true Es ?

- optically luminous
- high velocity dispersion
- boxy isophotes
- slow rotators
- flat cores
- high X-ray luminosity
- strong radio sources



Dynamical bimodality of ellipticals





Isotropic, round, slow rotators

Anisotropic, flattened, fast rotators

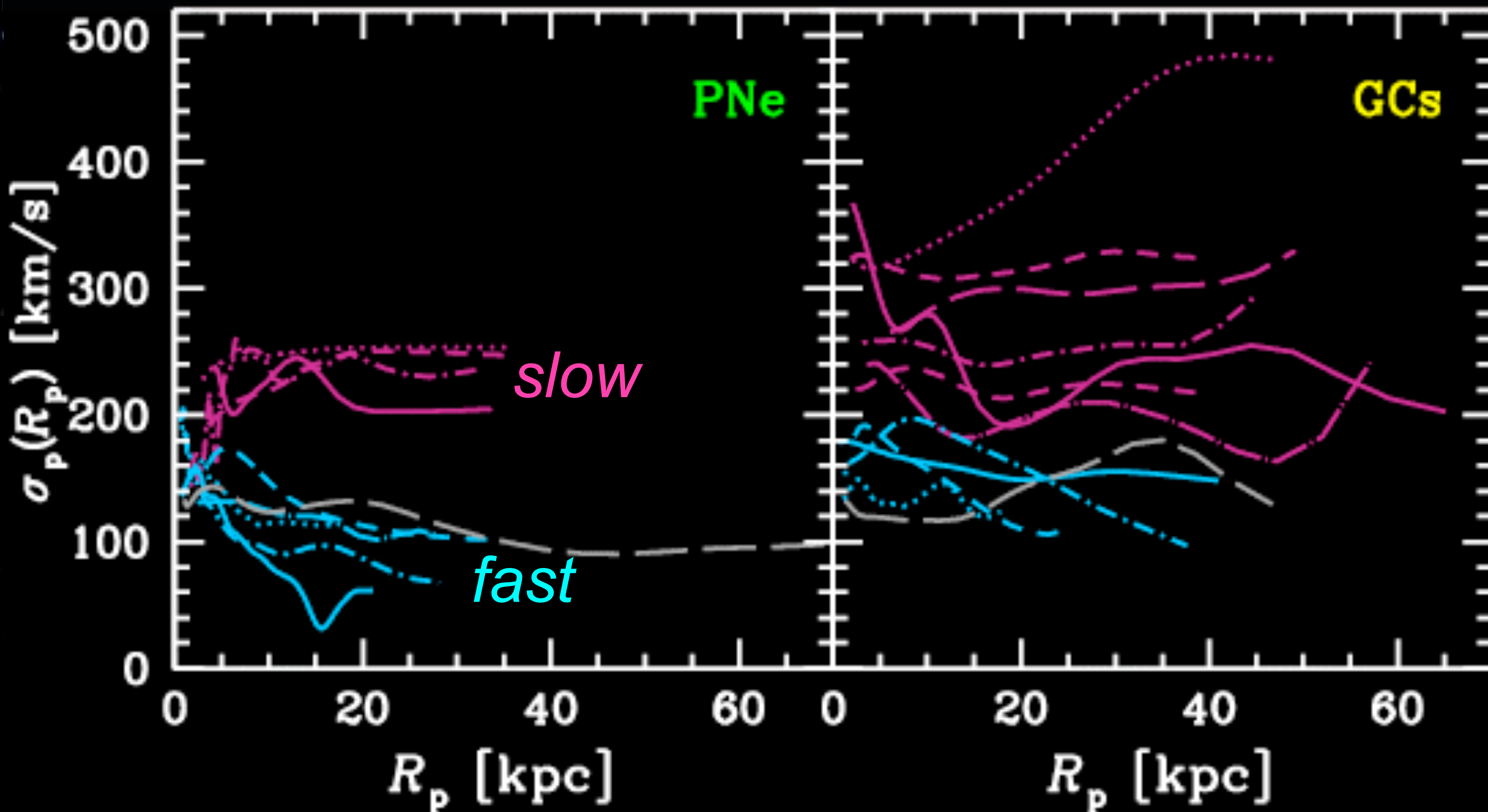
Early wet multiple mergers

Wet/dry pair major mergers

(Cappellari et al. 2007)

(Burkert et al. 2008)

Early-type halo velocity dispersions



- ***Bimodality*** *in PN velocity dispersions*

(Méndez et al. 2008; Coccato et al. 2009; Douglas et al. in prep.)

- *GCs similar but less dramatic*

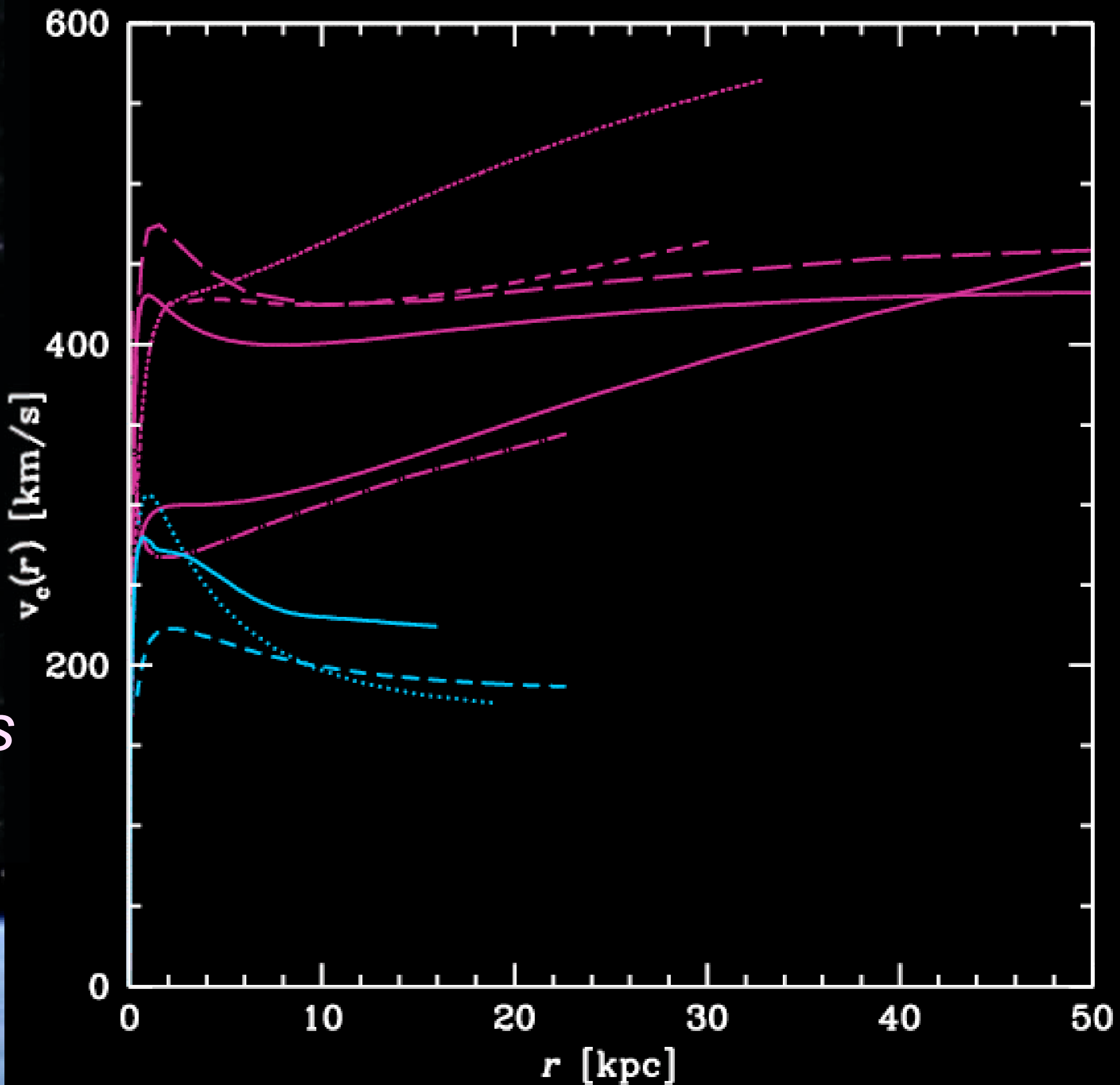
Early-type circular velocity profiles

Slow rotators:
flat/rising v_c

Fast rotators:
declining v_c

Romanowsky et al. (2003);
Douglas et al. (2007);
De Lorenzi et al. (2008, 2009);
Napolitano et al. (2009)

GC cross-checks support PN results in most cases



DM trends of early-type galaxies

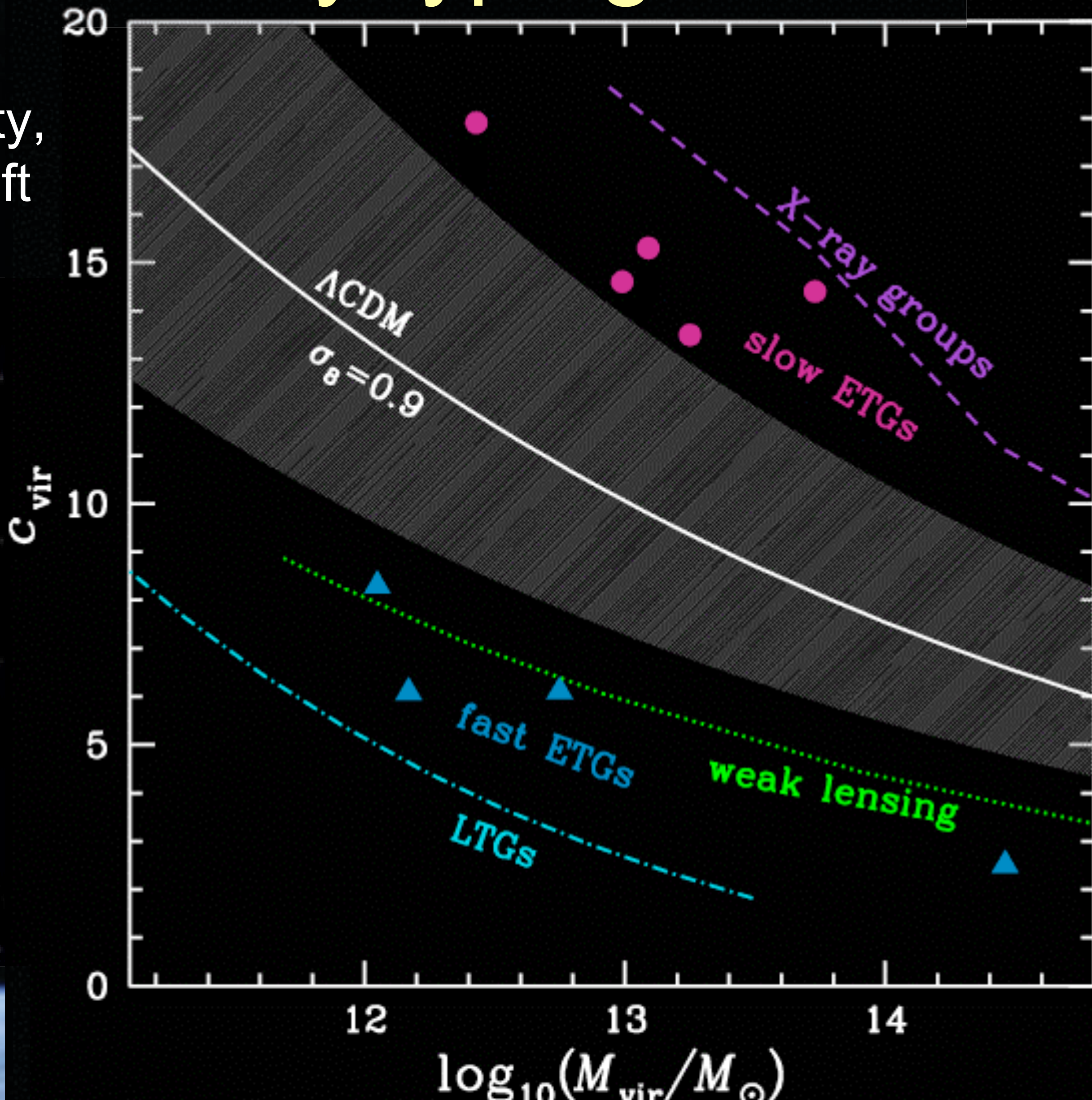
"concentration" c_{vir} parameterizes DM density, relates to collapse redshift
(Bullock et al. 2001)

systematic difference: slow, fast rotators (**opposite** DM, stellar concentrations)

ΛCDM prediction is "forbidden region"!

(Napolitano et al. 2009)

Low-c early-types from strong lensing, FP:
(Keeton 2001; Borriello et al. 2003)



Dark matter bimodality

Fast/slow rotator dichotomy not explainable via:

- smooth scalings with luminosity
- biasing with formation redshift
- biasing with angular momentum
- anti-hierarchical/downsizing DM (WDM, etc.?)
- dyamical modeling systematics (geometry/orbit structure)
- selection effects
- alternative gravitational dynamics (MOND, etc.)
- stellar populations modeling systematics

Could be due to:

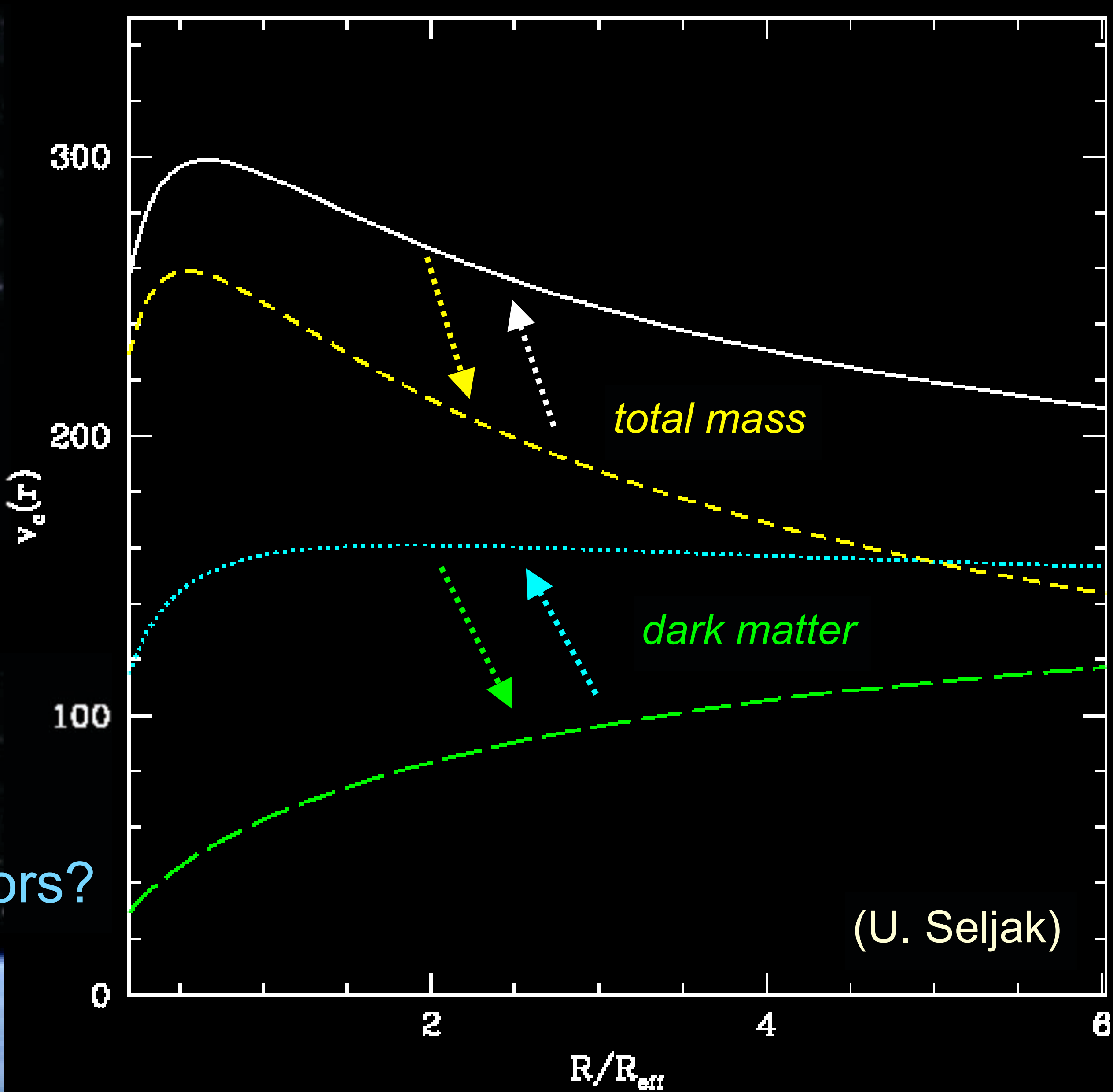
- baryonic physics (cooling, feedback, merger dynamics, etc.)
- environment (all slow rotators are group central?)

Further clues from halo rotation, orbits, GC properties

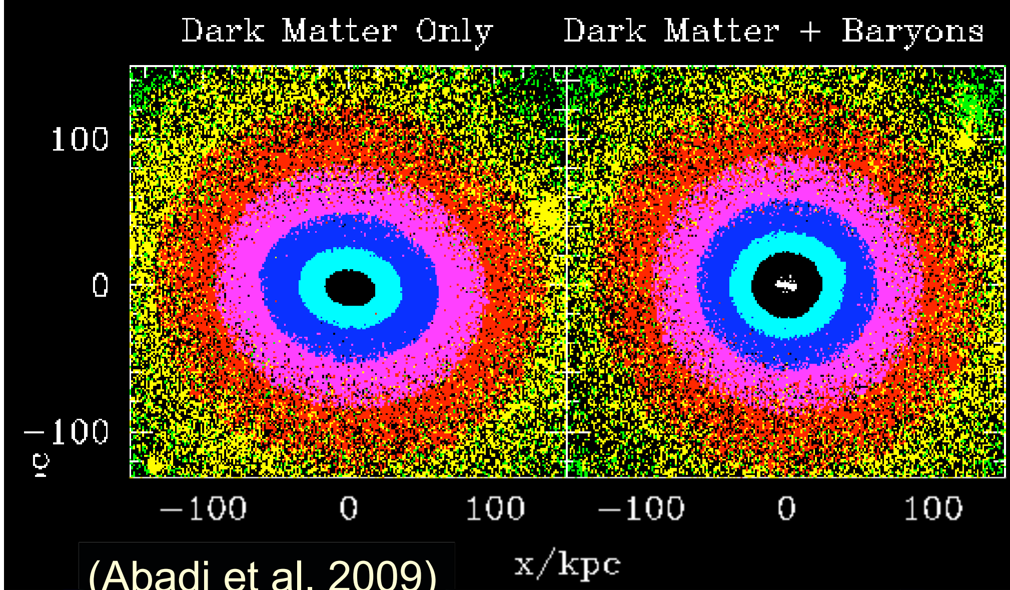
Baryonic effects on halo concentration

baryonic dissipation produces adiabatic contraction of halo
→ *increases*
central ρ_{DM}
(Blumenthal et al. 1986; Gnedin et al. 2004)
→ slow rotators?

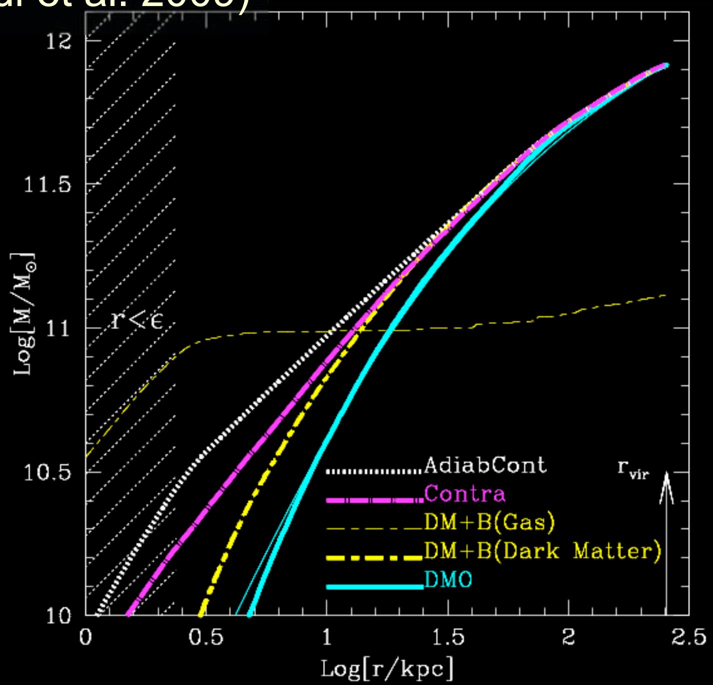
baryonic feedback expands halo ??
(Mo & Mao 2004)
→ spirals, fast rotators?



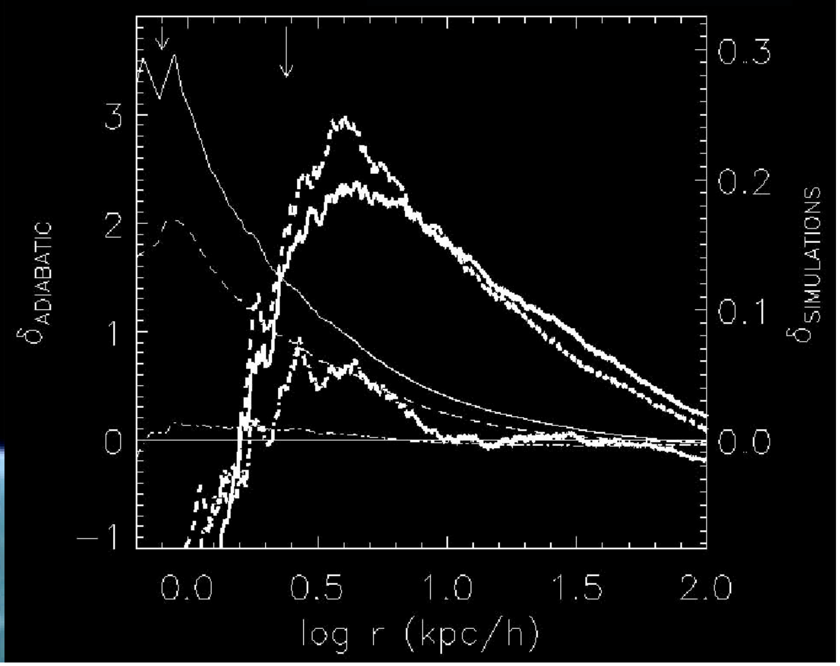
Baryonic effects on DM profile



(Abadi et al. 2009)



(Pedrosa et al. 2009)



DM bimodality from coupled merger histories + baryonic physics?

Fast rotators from $z < 1$ quenching and wet mergers (Faber et al. 2007) with substantial feedback to lower ρ_{DM}
– *lenticulars included, or 3rd family?*

Slow rotators from $z > 1$ quasi-monolithic collapse in high-overdensity regions with dissipation to raise ρ_{DM} (later dry merging also helps):
Blumenthal et al. (1984); Burkert et al. (2008);
but see Kang et al. (2007)
– *did all slow rotators form in group-mass halos?*

→ *Why two distinct episodes for early-type galaxy formation?*


• Data are improving…
• Models are improving…
• Theory is improving…
• Stay tuned for stronger constraints on dark matter!
SLUGGS